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1995

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Citation (APA):
Astrup, P. (1995). *Cyclone gasifier for biomass. Preliminary investigations*. Denmark. Forskningscenter Risoe. Risoe-R No. 833(EN)

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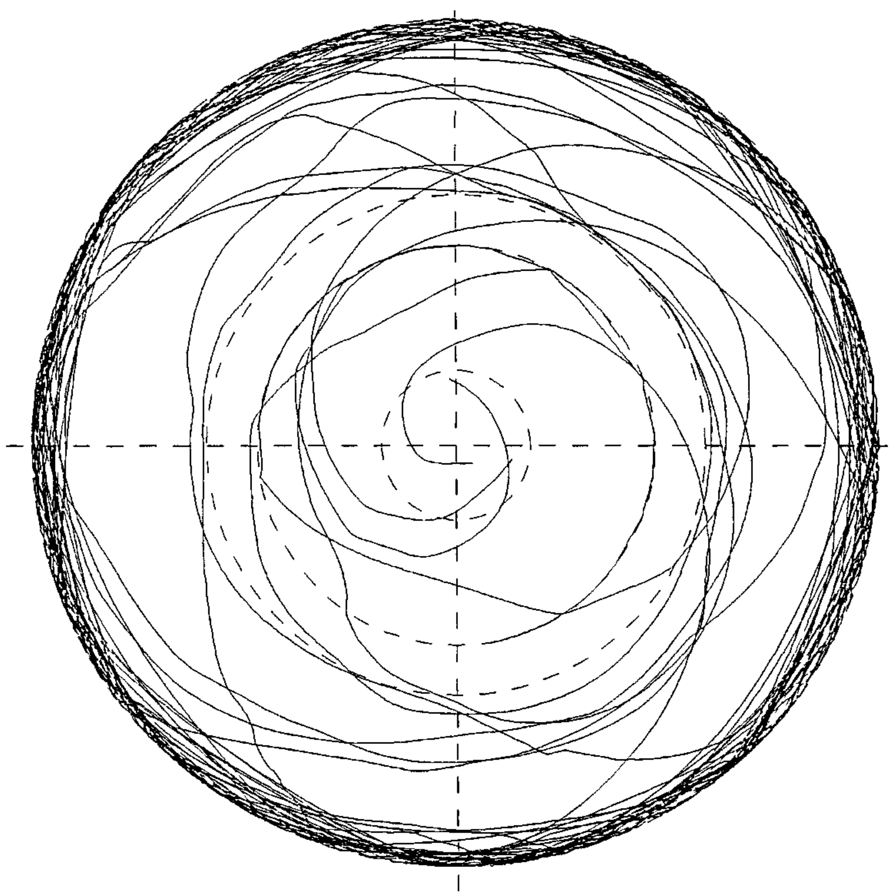
Risø-R-833(EN)

Cyclone Gasifier for Biomass

Preliminary Investigations

Poul Astrup



Risø National Laboratory, Roskilde, Denmark
July 1995

Cyclone Gasifier for Biomass

Risø-R-833(EN)

Preliminary Investigations

Poul Astrup

Risø National Laboratory, Roskilde, Denmark
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Abstract

Aiming at the design of a 20 MW as fired slagging cyclone gasifier for biomass, it has been investigated how biomass can or have to behave in such a device. This has included calculations for the slag flow, the heat loss, the gasification limits for char sitting in the molten slag surface, and fluid dynamics calculations for the gas and particle flows in a test case and in a proposed design. It has been found that it is unlikely that the char sitting in the slag surface can gasify at a rate equaling the feeding rate unless the cyclone is very large, that a high amount of char therefore has to stay in suspension somewhere in the cyclone and for a long time and that this may lead to a substantial carry over for the proposed design.

This work has been carried out as a part of the two projects: ENS-1323/93-0022, partly financed by the Danish Ministry of Energy, and JOU2-CT93-0434, partly financed by the European Commission, both named "Highly Efficient Conversion of Biomass to Power and Heat".

While the ENS project has been carried out by Risø National Laboratory, Department of Combustion Research, Denmark, and Vølund R&D Center, Denmark, the JOULE project has also had participation of Ansaldo Ricerche, Italy, and Conphoebus, Italy.

ISBN 87-550-2089-5
ISSN 0106-2840

Grafisk Service · Risø · 1995

Contents

1 Introduction

This work on biomass gasification in a slagging cyclone has been carried out in accordance with the two projects: ENS-1323/93-0022, partly financed by the Danish Ministry of Energy, and JOU2-CT93-0434, partly financed by the European Commission, both named "Highly Efficient Conversion of Biomass to Power and Heat". While the goal of the former was to study cyclone design and to find out if sufficient residence time for total gasification of straw particles can be obtained, the goal of the latter has been much wider, including characterization of biomass of different type and origin, development of a hot gas particle separator, performance studies of systems including a cyclone gasifier, a combustion chamber, an air to air heat exchanger, an air blown turbine, and a steam cycle, identification of critical components in such systems, design of biomass feeding systems, and as a subtask based on the results of the ENS project, design of a cyclone gasifier.

The ENS project has been carried out by
Risø National Laboratory, Department of Combustion Research, Denmark;
Vølund R&D Center, Denmark;
while the JOULE project also has had participation by:
Ansaldo Ricerche, Italy;
Conphoebus, Italy.

The present report only concerns the cyclone work and therefore only references the ENS project and the cyclone design subtask of the JOULE project. Parts of this report appear in both project reports, [17] and [11].

In order to investigate the possibility of using commercial fluid dynamics codes to obtain knowledge about straw behaviour in cyclone gasifiers the in house code CFDS-FLOW3D from AEA Industrial Technology [1] and the FLUENT code at Fluent Europe in Sheffield, England, were both tested against a cold gas flow cyclone case from the literature, Ohtake and Nakatake [15], and the in house developed particle flow code PAFCA [5] were applied for the particle calculations. The gas flow calcuations corresponded reasonably well with the data and the particle calculations showed that all particles except the finest shall reach the wall in short time if let in tangentially. The time of possible residence could however not be obtained.

With the cyclone run in slagging mode – a decision taken very early in the project – a particle hitting the wall was anticipated to stick to the molten slag so with the high mass fraction of particles suspected to hit the walls the behaviour of char sitting in the slag surface was investigated.
Based on a stoichiometric ratio of one half, an inlet air temperature of 600 °C, a straw feeding of 20 MW as fired, and the log law of the wall for velocity, temperature, and species concentration profiles near the wall, estimates were made for the slag layer thickness and surface speed, for the cyclone wall heat flux, and for the maximum gasification rate of char sticking to the slag.

The surface speed turned out always to be low and so to give ample time for gasification of the sticking straw char if it wasn't for the fact that a char layer sticking to a wall possesses no greater area for gasification agent diffusion than the wall area. The process gets diffusion limited. And with limited slag surface temperature also kinetic rate limitations come into play.

Unless the cyclone wall area and thereby the cyclone as such is very large, only a fraction of the char can gasify from the walls. Char will therefore pile up somewhere in the cyclone until gasification from wall and pile plus carry over plus lost with the slag equals the feed flow.

A cyclone layout was proposed for the 20 MW case and an initial fluid dynamics investigation was performed. This does indicate a possible problem with char carry over but much improvement have to be made to the codes in question if more precise information shall be gained.

2 Test of flow codes

In order to apply commercial fluid dynamics codes for the investigation of straw behaviour in cyclones, two such codes – the CFDS-FLOW3D from AEA Industrial Technology [1] and the FLUENT code at Fluent Europe in Sheffield, England – have been tested against gas flow data from a cyclone experiment, and their particle flow capabilities have been tested to different degrees. An in house developed particle flow code have also been tested.

2.1 Experiment

The experiment in question was taken from the literature, Ohtake and Nakatake [15], who presents a series of cold flow measurements on a cyclone furnace model. One of their cases was selected because of the relative simple geometry of their model, the high degree of axial symmetry with inlets at every 90° around the periphery and because these experiments concern a model of a cyclone furnace rather than of a cyclone particle separator.
Sketches of the cyclone are shown in figure 1. It is a 290 mm diameter, 900 mm long cyclone with eight 20 mm diameter inlet tubes, four placed 30 mm below the top, the other four 100 mm above the bottom, and all angled 30° with respect to the diameter through the attachment points. At the top of the cyclone a small central piece of tube contains a spray nozzle for spraying water into the system to simulate molten slag and at the bottom a 200 mm diameter outlet tube is connected. The length of the outlet tube and how it ends is not obtainable from Ohtake and Nakatake [15] and the dimensions and form sketched are those used for the calculations. The inlet flow is 300 m^3/h equally distributed between the eight inlets and the experimental data consists of profiles of tangential velocities versus radius at the four axial positions 100, 300, 500 and 700 mm below the top. These positions are called stage 1, 2, 3 and 4.

2.2 Gas flow calculations

CFDS-FLOW3D

For the calculations with the FLOW3D code the cyclone was modelled 2D-axis-symmetrically, ie the calculations were performed on a single axial-radial plane in the cyclone. In doing so, the tangential inlets were modelled as distributed all around the periphery and to get the right inlet area they therefore had to be squeezed axially. The correct area was necessary for getting both mass and

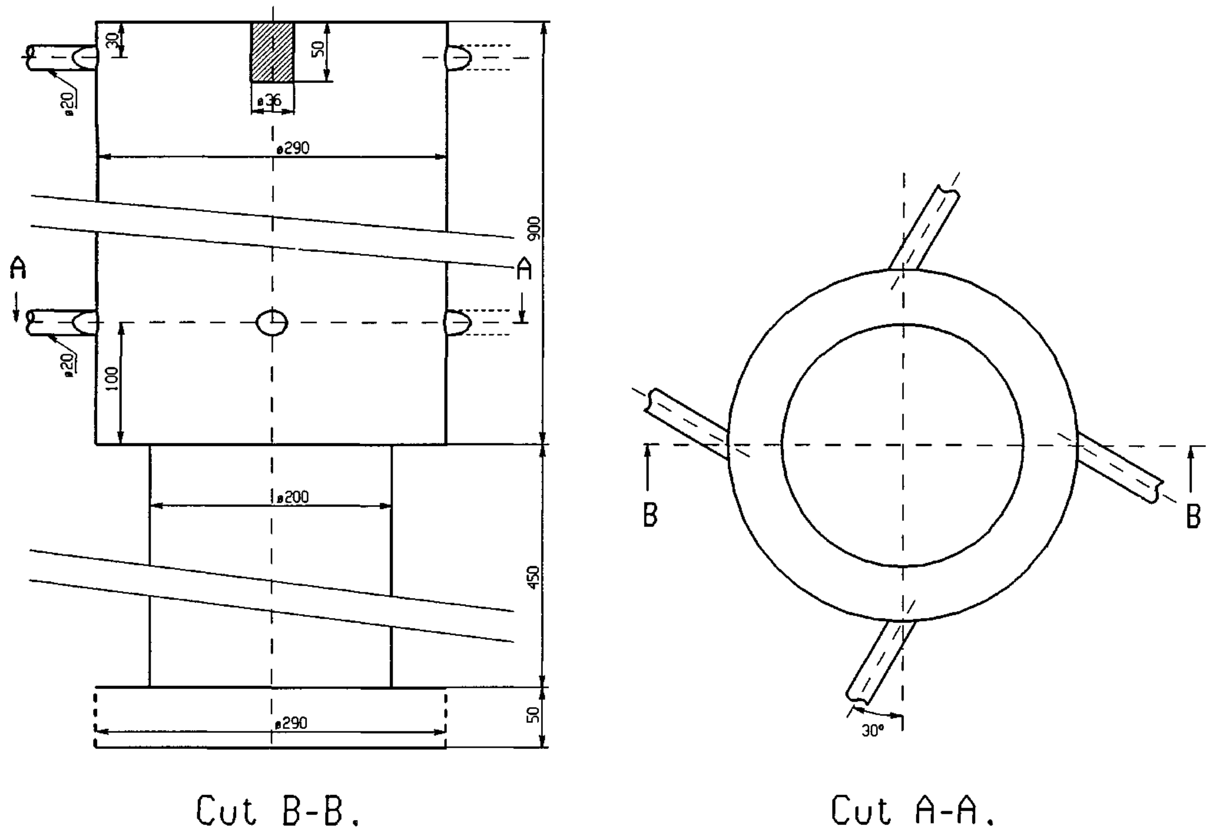

Figure 1. Sketch of cyclone from Ohtake and Nakatake [15].

momentum flow correct.

The code had difficulties in reaching a really converged solution. The error residuals didn't drop continuously with increasing number of iterations but went oscillating at some point and stayed so. With the Reynolds stress turbulence model applied the eventual mass error residual was comparable to the flow through the cyclone ie 0.04 to 0.06 kg/s versus the flow of 0.098 kg/s. Figure 2 shows the mass error residuals for the first 5000 iterations of the initial k–ϵ calculation and for the last 5000 iterations of the final Reynolds stress calculation.
The mass error residual is only a measure for how well the code reaches a fully converged solution, it has nothing to do with the overall mass balance for the cyclone which cannot be violated in a steady state calculation. From experience with the much more simple TEACH-T code [9], a mass error residual of 10^{-5} times the cyclone flow was expected obtained with no other problems than a high CPU consumption. Again from experience with the TEACH-T code it is also known that the flow fields obtained do not change much with the decreasing error residuals so the results are not necessarily bad, in fact they are reasonably good.
The calculated tangential velocities compare qualitatively well with the experimental data showing the measured form of a Rankine vortex in the outer half of the cyclone. Quantitatively they are however somewhat low, see figure 3.
Figure 4 shows the used nodalisation, a vector plot of the velocities projected upon the calculational plane and a contour plot of the corresponding normalized

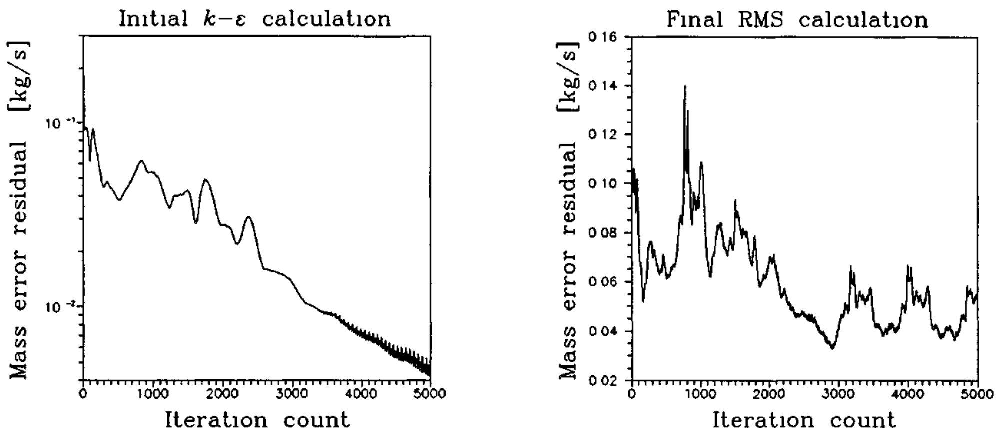

Figure 2. FLOW3D mass error residuals as function of iteration count.

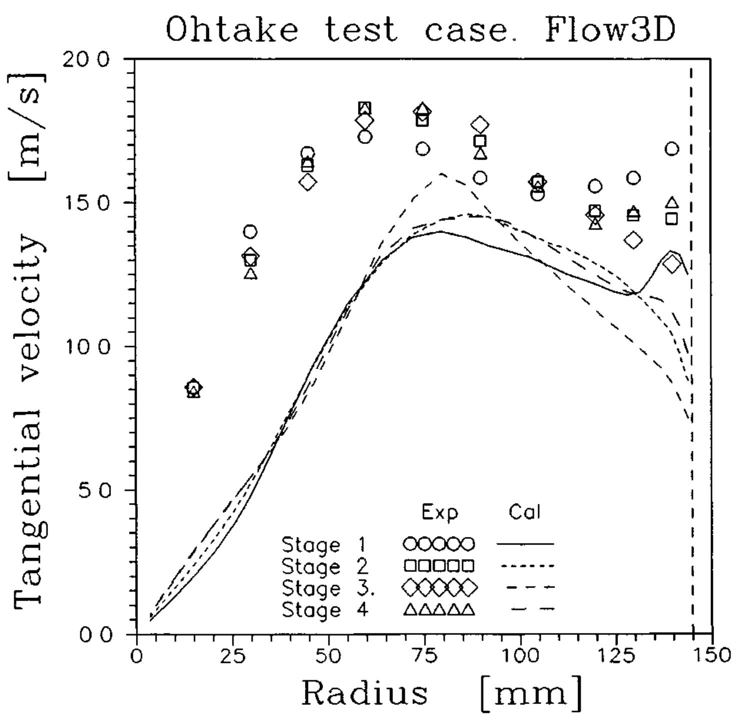

Figure 3. Comparison of FLOW3D calculation with experimental data.

stream function ie the stream lines.

Fluent

Based on good experience with earlier orders on flow calculations from Fluent Europe Ltd in Sheffield, England, it was decided to investigate, if also cyclone calculations could be bought from there with profit.

In order to compare with the FLOW3D calculation a calculation of the above mentioned cyclone case was ordered. Their choice was to do a fully 3D calculation and to use a Reynolds stress turbulence model. The results of that calculation were unphysical, however, showing tangential velocities of different sign for the

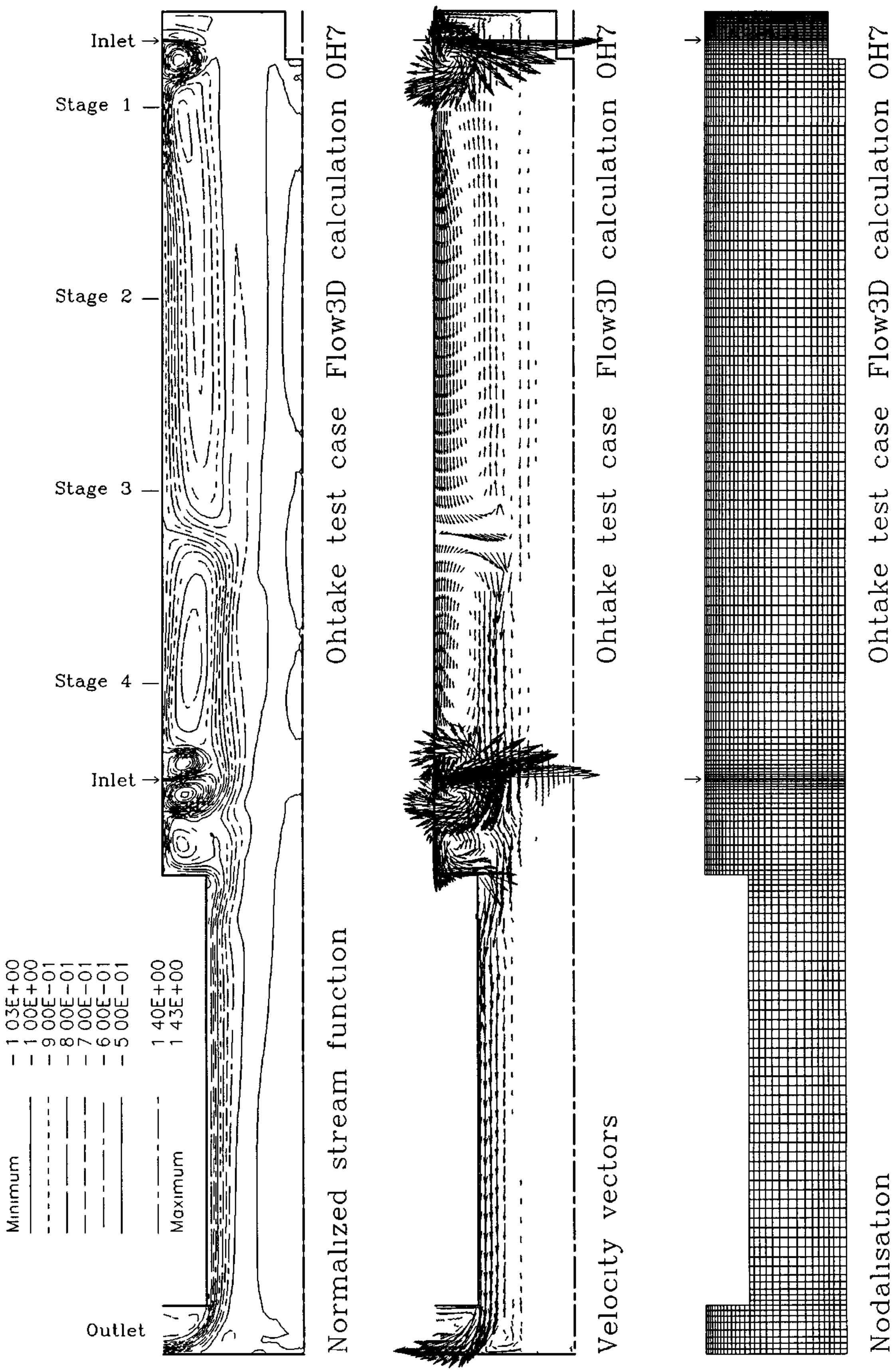

Figure 4. FLOW3D. Nodalisation, velocity vectors and streamlines.

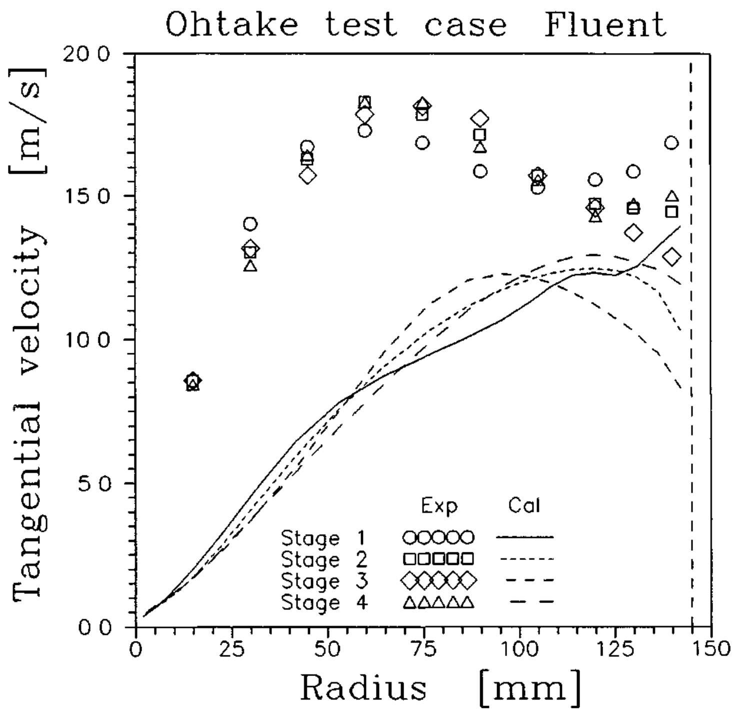

Figure 5. Comparison of Fluent calculation with experimental data.

central half and outer half of the cyclone.
In a second attempt they did two things to avoid further problems: they excluded the central axis by applying a minimum radius of 1 mm, and they used a turbulence model based on renormalization group theory in stead of the Reynolds stress model. The one millimeter inner radius should not affect anything, but the renormalization group turbulence model creates results that look very much like the results from a k–ϵ calculation, ie solid body rotation almost all way from the center to the wall in stead of a Rankine vortex in the outer half of the cyclone, see figure 5.

With a full 3D calculation the inlets can be modelled more correctly and the evolution with tangential position can be investigated. Figure 6 shows the nodalisation used by Fluent plus velocity vector plots at three tangential positions ie at an inlet plane and 30° and 60° downstream.

2.3 Particle calculations

CFDS-FLOW3D

The particle tracking model of FLOW3D did not function properly unless the restitution factor for particle bouncing on walls was set to zero, ie particle capture at first collision with the wall. This may be a sufficiently good model when only a limited fraction of the fuel reaches the wall. For straw in a slagging cyclone it is not good. Furthermore FLOW3D includes models for spherical particles only and the output just consists of particle position and velocity versus time.

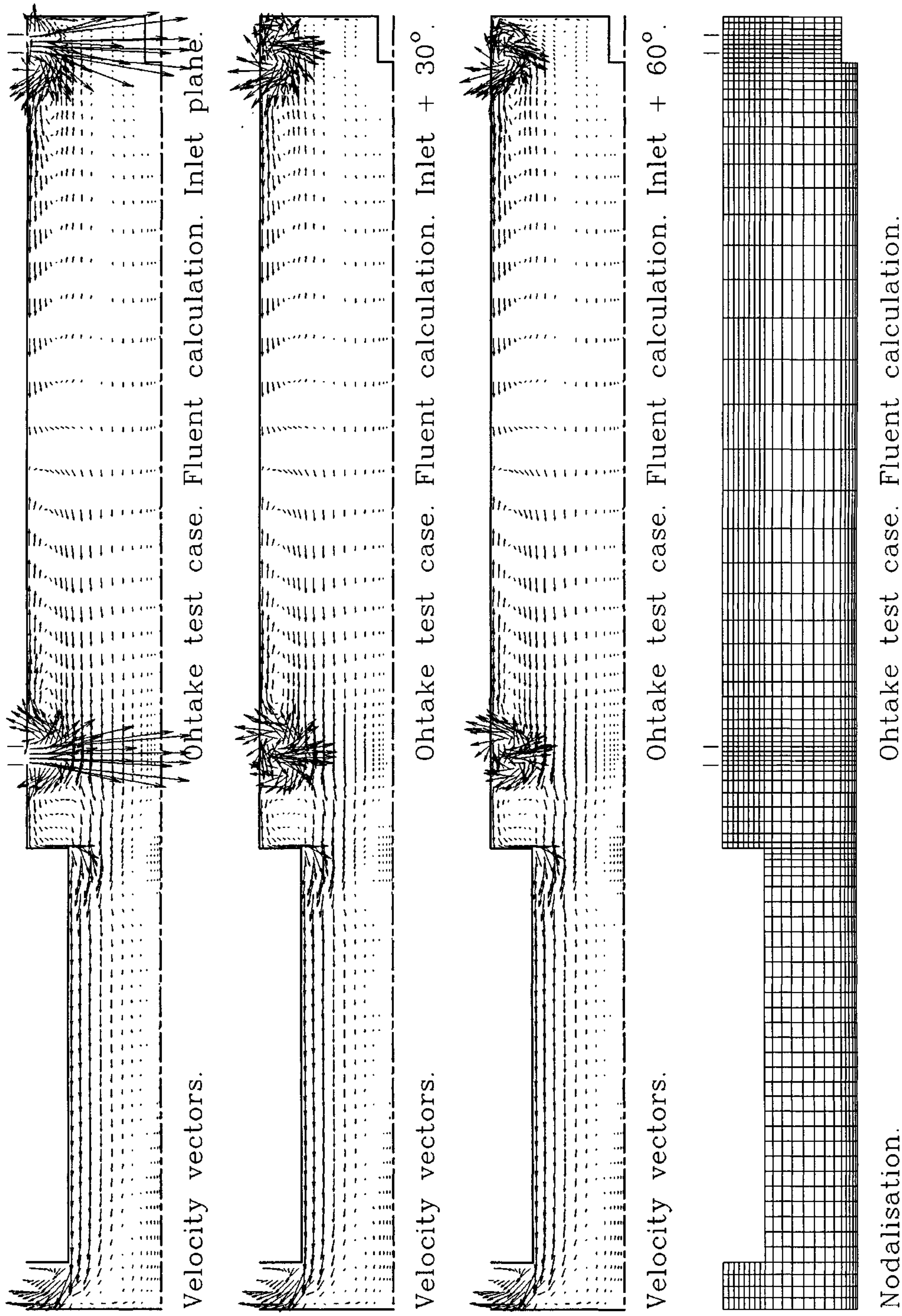

Figure 6. Fluent. Nodalisation and velocity vectors at three tangential positions.

Fluent
Fluent Europe wasn't asked to do more than a single particle track and that with a 3 mm diameter particle heavy enough to just follow a straight line from the inlet to the wall where the calculation stopped.

PAFCA
In order to get decent particle calculations, the 2D axisymmetric version of the PAFCA code - PArticle Flow CAlculations [5] - developed at Risø National Laboratory, was updated to cope with swirl cases. This code reads the gas flow fields calculated by a gas flow code, here FLOW3D, and tracks particles through the flow domain allowing for the influence of the turbulence.
It works well with any restitution factor between zero and one and can be easily reprogrammed to include flow resistance and other correlations specific to straw or other kinds of biomass (if they can be found) in stead of those of a perfect sphere presently included. The code allows the particles to follow specified distributions or distribution functions for size, position and velocity at the inlets, and based on the calculated tracks it determines particle volumetric concentrations, mean velocities and velocity fluctuations, and calculation of other interesting variables can be implemented.

Figure 7 shows four plots with each 100 particle tracks. The particles are spheres of density 120 kg/m^3 and diameter as indicated. The wall collision restitution factor is 0.316 for the particle bounce back velocity ie 0.1 for the kinetic energy and the tracing of the individual particle is stopped when the particle escapes through the outlet, when it hits the same wall twice in two consecutive timesteps or after maximum 20 seconds of flying. All particles are let in through the upper inlet and with velocities distributed around the gas mean velocity. No two particles get the exact same start unless the distribution width is set to zero.
The somewhat strange look of the tracks is caused by the influence of turbulence plus the fact that the tangential motion is invisible on these plots. It is seen how the increasing diameter makes the particles concentrate more and more towards the wall. But notice the particle size. These particles are very small compared to 50 mm long pieces of straw, very very small. Although this cyclone has a small radius the calculations indicate that the very large part of straw entering a cyclone at 33 m/s as here stays at the wall until it is burned or gasified whatever the wall is dry or wetted with molten slag. Due to turbulent bursts or perhaps just to roughness of the wall smaller particles can be reentrained and carried further by the gas stream.
Only few particles leave the cyclone in these calculations, most are stopped on the twice hitting the wall criteria. The mean time of flight has been found to 0.27, 0.34, 0.33 and 0.44 seconds for the 0.005, 0.01, 0.02 and 0.05 mm diameter particles respectively but as most particles stop on the wall these numbers do not represent obtainable residence times.

3 Straw fired 20 MW cyclone

Bue to the knowledge gained from the code calculations that particles of sizes likely to be encountered when straw is fired travel to the wall, and to the antic-

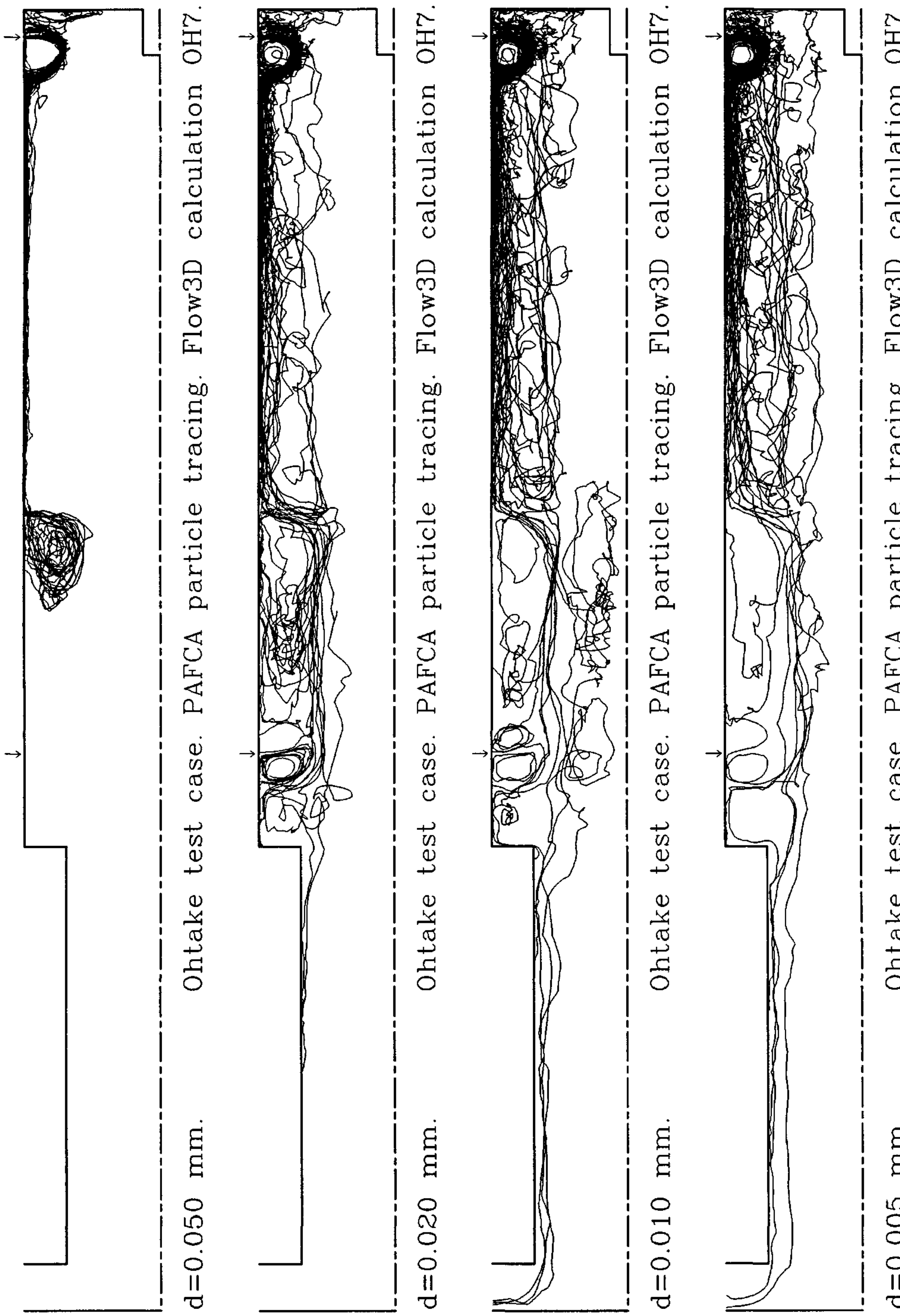

Figure 7. PAFCA calculations of particle tracks.

ipation that particles hitting the wall in a slagging cyclone should stick to the slag, the cyclone wall zone has been investigated.
This has included combined calculations for the slag flow on the walls and the heat transfer through these, and calculations of the gasification possibilities for char sitting in the slag.
All calculations presented have been based on a 20 MW straw fired cyclone of around 2 m diameter, a stoichiometric coefficient of 0.5, and a gasification air temperature of 600 °C. The calculations of heat and mass transfer from bulk to wall have been based on turbulent boundary layer theory, described in appendix A, and the radiative heat flux from bulk gas to walls has been taken into account. The tangential velocity profile has been estimated from literature data.

4 Mass flows and composition

The data used for the straw can be seen from the spreadsheet calculation of stoichiometric combustion given in table 1.

Product calculation for stoichiometric combustion.

Component	Relativ mass dry	Mass fraction dry	Product	Kg O2 pr kg reactant	Kg O2 pr kg dry fuel	Kg product pr kg dry fuel
C:	0.4598	0.4598	CO2:	2.6667	1.2261	1.6859
H:	0.0575	0.0575	H2O:	8.0000	0.4600	0.5175
O:	0.4138	0.4138		-1.0000	-0.4138	0.0000
N:	0.0046	0.0046	N2:	0.0000	0.0000	0.0046
S:	0.0011	0.0011	SO2:	1.0000	0.0011	0.0022
Ash:	0.0632	0.0632	Ash:	0.0000	0.0000	0.0632
Sum:	1.0000	1.0000			1.2734	2.2102 + ash

Fuel water	Mass fraction	Q,gross dry MJ/kg	Q,gross wet MJ/kg	Q,net dry MJ/kg	Q,net wet MJ/kg
H2O:	0.1500	18.2700	15.5295	16.9763	14.0548

Product gas = dry air - O2 + products + fuel water.

Component	Dry air Mass fraction	Dry air Kg pr kg dry fuel	Products Kg pr kg dry fuel	Products Kmol pr kg dry fuel
CO2:	0.0005	0.0028	1.6887	0.0384
H2O:	0.0000	0.0000	0.6940	0.0386
O2:	0.2314	1.2734	0.0000	0.0000
N2:	0.7552	4.1560	4.1606	0.1486
SO2:	0.0000	0.0000	0.0022	0.0000
Ar:	0.0129	0.0709	0.0709	0.0018
Sum:	1.0000	5.5031	6.6164	0.2273

Table 1. Stoichiometric combustion of straw.

With a volatility of 75% of the dry matter and a specified fuel feed of 20 MW as fired, the following is deduced for the mass flows:

$$\dot{m}_{\text{wet straw}} = 1.423 \text{ kg/s} \quad (1)$$
$$\dot{m}_{\text{dry straw}} = 1.210 \text{ kg/s} \quad (2)$$
$$\dot{m}_{\text{fuel water}} = 0.213 \text{ kg/s} \quad (3)$$
$$\dot{m}_{\text{volatiles}} = 0.907 \text{ kg/s} \quad (4)$$
$$\dot{m}_{\text{char carbon}} = 0.226 \text{ kg/s} \quad (5)$$
$$\dot{m}_{\text{ash}} = 0.0764 \text{ kg/s} \quad (6)$$

The air flow for gasification with half stoichiometric air becomes

$$\dot{m}_{\text{dry air}, \lambda=0.5} = 3.329 \text{ kg/s} \quad (7)$$

Gasification of high volatile fuel with air may proceed as follows: First does the volatile matter gas off leaving char particles of carbon and ash, next does the volatiles react to equilibrium with the available air, and finally does the char carbon gasify with the above mentioned equilibrium products.

For the volatile gas of the straw presented in table 1 the mass fractions of the constituents are the following: $\gamma_C = 0.364$, $\gamma_H = 0.0767$, $\gamma_N = 0.0061$, $\gamma_S = 0.0015$, $\gamma_O = 0.5517$, and the high heating value is approximately 16.2 MJ/kg.

For the volatile mass flow of eq. 4, the water flow of eq. 3, the air mass flow of eq. 7 and an air temperature of 600 °C, the adiabatic equilibrium is calculated with a program using the method of Gibbs free energy minimization, programmed and described by Fjellerup [8]. The resulting temperature and species fractions are given in table 2.
Equivalent results after gasification of the char carbon as given by eq. 5 are also presented in table 2.

	Devolatilization	Gasification
Temperature [°C]	1907	1474
Mole fractions		
[H_2]	0.01732	0.08981
[CH_4]	0.00000	0.00000
[H_2O]	0.26304	0.16183
[CO]	0.04209	0.16725
[CO_2]	0.12433	0.08435
[O_2]	0.00023	0.00000
[H_2S]	0.00025	0.00021
[COS]	0.00001	0.00002
[N_2]	0.55273	0.49654

Table 2. Adiabatic equilibrium after devolatilization and after gasification.

5 Tangential velocity profile

In order to estimate a decent velocity profile as a base for calculations of heat and mass transfer to the cyclone wall, the data of Ohtake and Nakatake [15] has been used. Their data are excellently fitted by a third order polynomial in the radial distance, zero at the center, maximum at half radius and 0.7 $\times$ maximum at full radius, see figure 8, left.

Near the wall the velocity of the turbulent gas necessarily has to follow a logarithmic profile and at the wall a linear profile, ie the log-law of the wall applies. Figure 8, left, shows the data, the third order polynomial from the center to near the wall and two logarithmic profiles close to the wall, the one specified to smoothly join the polynomial, dashed, the other to be a factor 20 steeper than the polynomial, where they meet. While the first gives a wall friction very close to the one earlier calculated with the CFDS-FLOW3D code the latter better describes the data and gives rather much higher heat and mass transfer coefficients. So this is the one used in the following. The maximum velocity of 18 m/s for the data is around 54% of the velocity in the inlets. For the calculations for the 20 MW cyclone a maximum speed of 40 m/s is used. The used profile is shown as figure 8, right.

The exact meeting point of polynomial and log profile depends upon the kinematic viscosity of the gas and the gas properties used are those for the equilibrium gas after gasification as given in table 2 although calculated for a temperature of 1400 rather than 1474 °C.

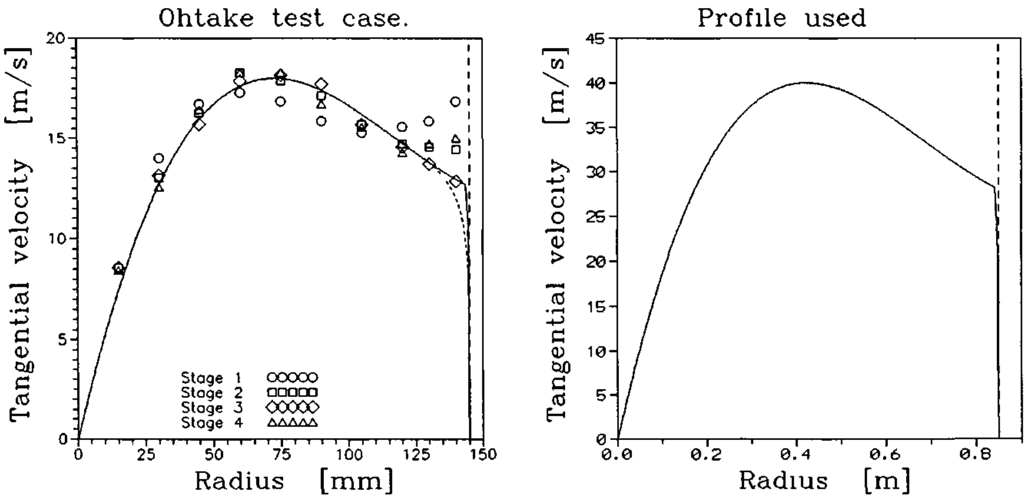

Figure 8. Left: Ohtake test case with curve fits.
Right: Tangential velocity profile used for the 20 MW cyclone.

6 Flow of slag and heat

In order to control the wall steel temperature a cyclone wall layout principally as sketched in figure 9 has been proposed by Vølund. The idea is to pass the gasification air and possibly also an amount of combustion air through the air heater annulus surrounding the cyclone walls, so cooling these without thermodynamic losses.

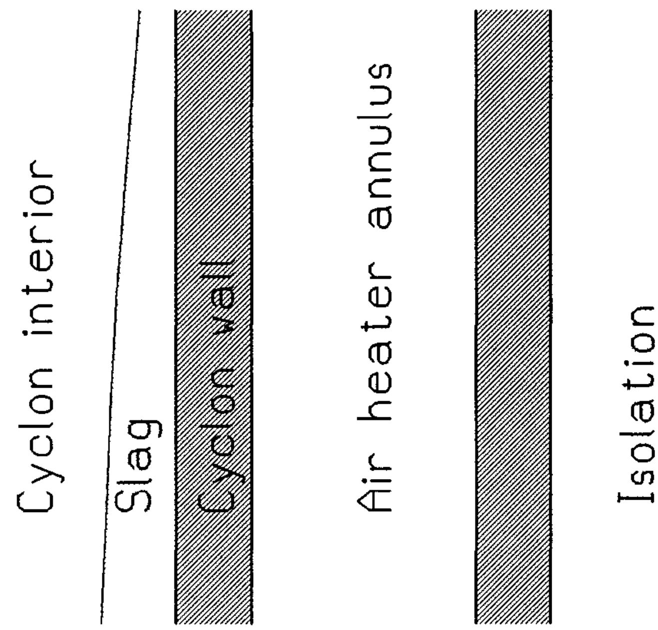

Figure 9. Geometry of considered cyclone wall.

With the limitation that the wall is vertical, whereby the whole problem can be handled onedimensionally, the slag thickness and surface velocity, the slag and steel temperatures and the heat flow to the air in the air heater annulus have been calculated for a base case and for some variation of slag mass flow, slag viscosity, slag heat conduction coefficient and air heater annulus air flow.

Model

For the heat transfer wall to air heater annulus air, the well known correlation

$$Nu \; = \; 0.023\, Pr^{0.4}\, Re^{0.8} \tag{8}$$

is used. On the inside ie from the process gas to the slag surface, the convective heat transfer is calculated from the analogy between diffusion of heat and of momentum as described in appendix A. For the radiative heat transfer, that from gas to slag is modelled with the mean beam length model of Hadvig [10] but no particle radiation is taken into account. The slag emissivity is set to 1.

The slag velocity equation is integrated from the wall towards the surface using the standard 4th order Runge-Kutta method and 20 steps through the slag layer with iteration in the layer thickness till the calculated mass flow equals that specified.

While the density and heat conduction coefficient have been kept temperature independent the dynamic viscosity has been taken as a function of the local slag

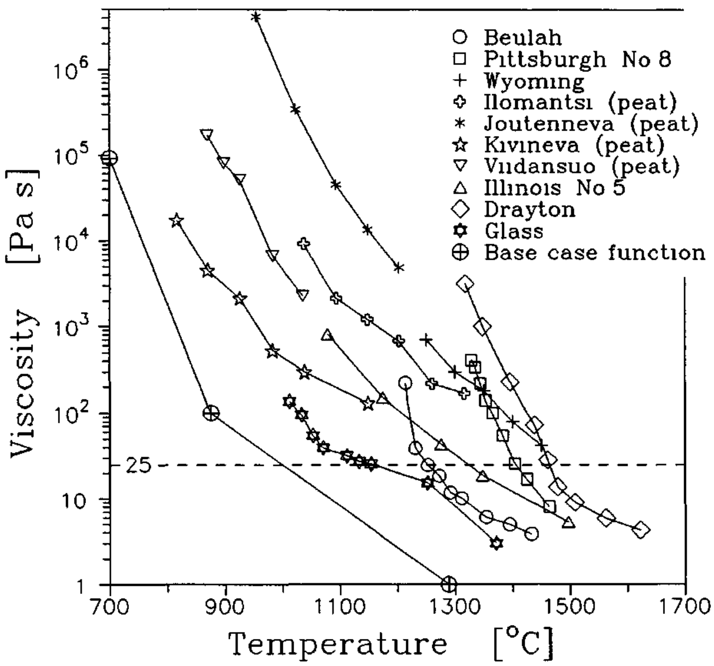

Figure 10. The base case viscosity function compared to those for five coal and four peat ashes and for an unspecified glass. From Andersen [3]. Reproduced with permission.

temperature, but due to lack of data for slag, data obtained from a glass data base [2] have been used for the modelling. In figure 10 the viscosity function used for the base case is compared to slag viscosities of five coals, four peats and an unspecified glass.

Calculations

The input data for the base case is given in table 3.

To investigate the relative influence of some of the variables and unknowns in question a sensitivity study has been performed varying a single input parameter at a time. Defining the ratio between the actual value and the base case value of the varied parameter as the parameter index, the results have been plotted against this index.

As an example calculations have been performed with a slag mass flow index between 0.2 and 2.0 which means that the slag mass flow has been varied from 0.2 to 2.0 times the base case value of 0.0764 kg/s, while all the other input parameters have been kept at the base case values.

The slag viscosity index has been varied between 0.1 and 10000.0, the slag heat conduction index between 0.2 and 2.0, and the air heater annulus air flow index between 1.0 and 3.0.

The results are presented in figures 11 and 12, where TSS, TSW and TWG mean temperature of slag surface, of slag-wall interface and of wall-gas (air heater annulus) interface respectively.

As seen from the temperature plots, the wall temperatures get rather high under

```
@  Base case input
@  ---------------
@               Data for the cyclone:
@               ---------------------
  0.85          RCYC     Cyclone radius                    [m]
  2.90          ZCYC     Cyclon length                     [m]
  0.03          FS       Width of air heater annulus       [m]
  0.01          WS       Thickness of wall                 [m]
 17.5           WK       Wall heat conduction coefficient  [W/mK]
@
@               Data for the gas in the cyclone:
@               --------------------------------
 1400.0         TGC      Process temperature               [°C]
 0.1827         RHOGC    Density                           [kg/m^3]
 1519.0         CPGC     Cp                                [J/kgK]
 4.323E-05      GMYC     Dynamic viscosity                 [kg/ms]
 0.08144        GKC      Heat conduction coefficient       [W/mK]
 0.16183        PH2O     H2O partial pressure              [bar]
 0.08435        PCO2     CO2 partial pressure              [bar]
 40.0           WMAX     Max tangential gas velocity       [m/s]
 20.0           DURATI   Ratio between steepness of
@                        log-profil and third order
@                        polynomium at the meeting point.
@
@               Data for the gas in the air heater annulus:
@               -------------------------------------------
 600.0          TGF      Temperature                       [°C]
 0.3990         RHOGF    Density                           [kg/m^3]
 1112.0         CPGF     Cp                                [J/kgK]
 3.856E-05      GMYF     Dynamic viskosity                 [kg/ms]
 0.05820        GKF      Heat conduction coefficient       [W/mK]
 3.329          GMPRKF   Mass flow                         [kg/s]
@
@               Data for the slag flow:
@               -----------------------
 0.0764         SMPRIK   Total slag flow                   [kg/s]
 1.0            XSMPRK   Minimum fraction considered
 0.1            DXSMPR   Step in fraction
 20             NS       Number of slag layer nodes
@
@               Model values for the slag:
@               --------------------------
 2760.0         RHOS     Density                           [kg/m^3]
 1.5            SK       Heat conduction coefficient       [W/mK]
5.7167266E+16  -0.0387961     SA(1)  SB(1)                 [kg/ms]  [1/°C]
1.7434474E+06  -0.0111505     SA(2)  SB(2)                 [kg/ms]  [1/°C]
@ Dynamic viscosity: μ(T) = MAX(SA(1)*EXP(SB(1)*T),SA(2)*EXP(SB(2)*T)) [kg/ms]
```

Table 3. Slag and heat flow. Input for base case.

these circumstances and they are rather little affected by the varied parameters. At the same time the slag surface temperatures are rather low as seen from a gasification kinetics viewpoint.

The heat flux through the wall seems mostly affected by the air heater annulus air flow ie. by the heat transfer coefficient on the annulus side of the wall.

The slag thickness stay low and so does the slag surface velocity. Only for slag viscosities one to ten thousand the nominal, things start to deviate, but such high viscosities are probably unlikely.

A ceramic liner on the wall would decrease the steel temperature and might increase the slag surface temperature.

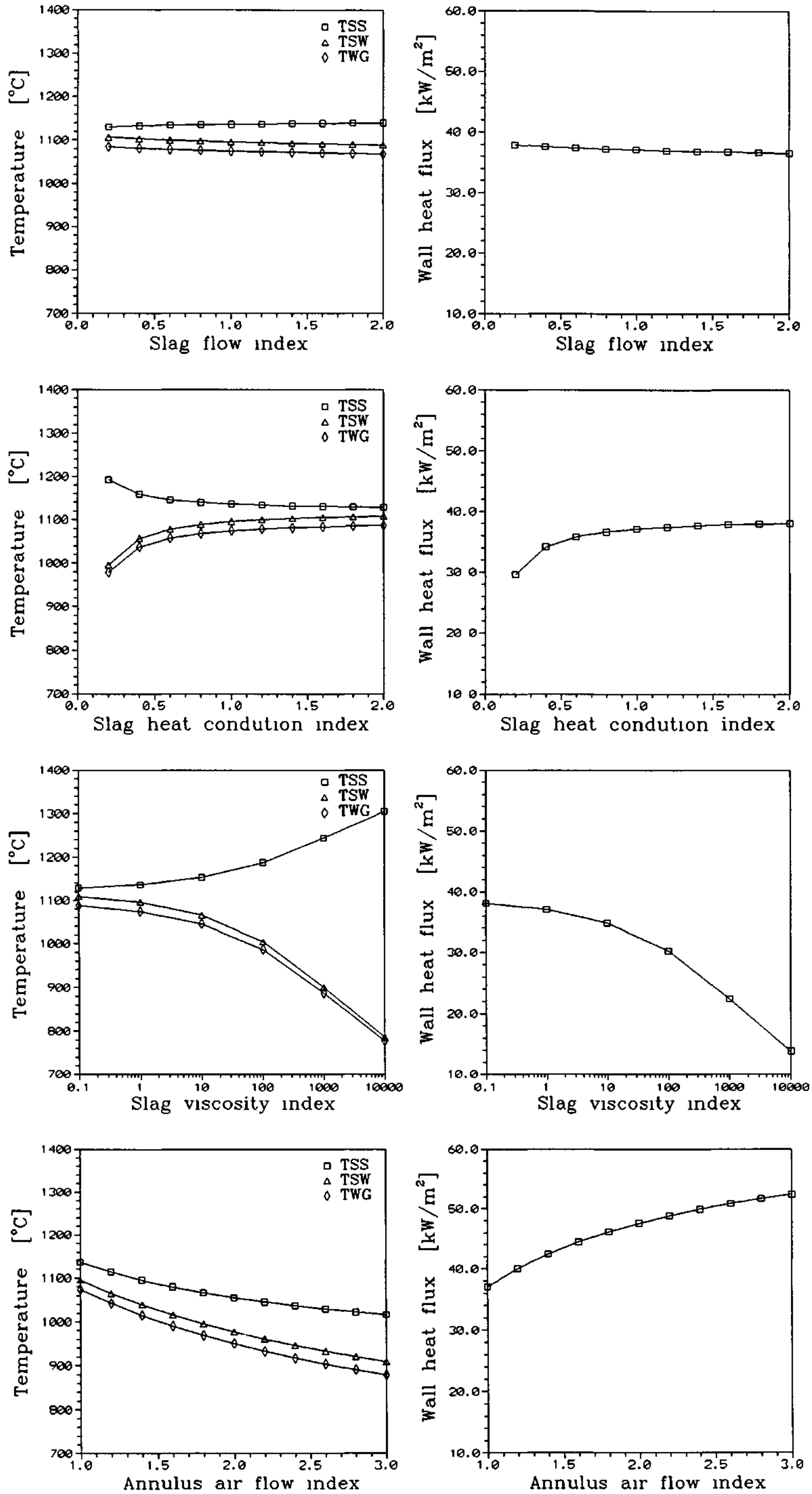

Figure 11. Influence of slag mass flow, slag heat conduction, slag viscosity and air heater annulus air flow upon the slag and wall temperatures and the wall heat flux.

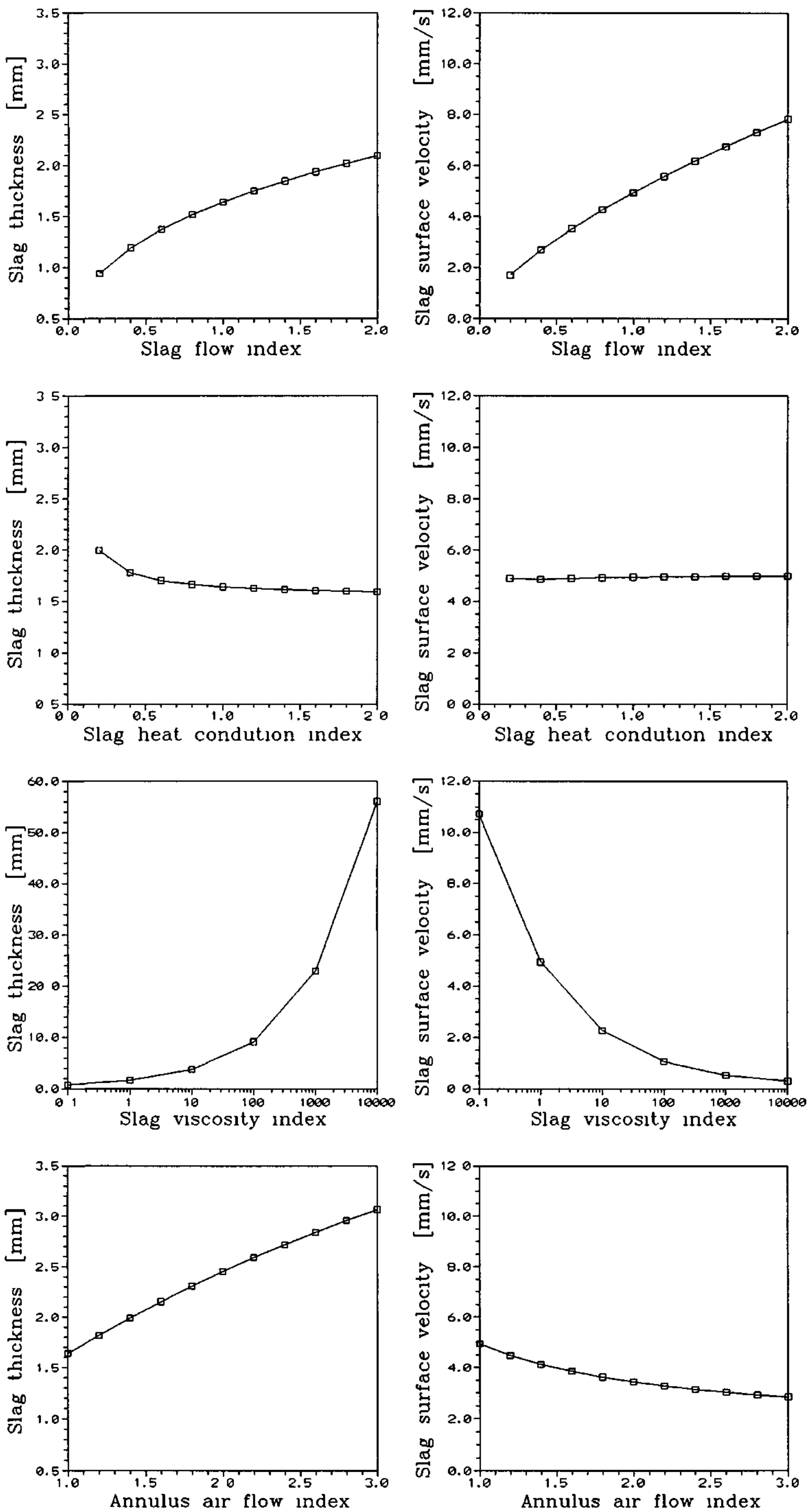

Figure 12. Influence of slag mass flow, slag heat conduction, slag viscosity and air heater annulus air flow upon the slag thickness and the slag surface velocity.

7 Gasification

The rate of gasification of char is determined by the reaction kinetics and by the diffusion of gasification agents to the char surface. For small particles at low temperatures the rate is typically reaction kinetic controlled while for large particles at high temperatures it its diffusion controlled.

7.1 Mass diffusion to a wall

As explained in appendix A the diffusion of heat and species to the wall can be calculated from known corresponding values of distance from the wall y, velocity u, temperature difference $T - T_w$, and mass fraction difference $\gamma - \gamma_w$ which in the diffusion limit where $\gamma_w = 0$ equals γ. Index w indicates values at the wall.

For the present case, the mass fractions for CO_2 and H_2O are taken as the mean of the equilibrium values after devolatilization and after gasification. Table 2 gives the mole fractions from which the mass fractions are calculated. These become $\gamma_{CO_2} = 0.175$ and $\gamma_{H_2O} = 0.145$. With $u_{max} = 40$ m/s the polynomial used to fit the velocity profile goes towards 28 m/s at the wall so $u = 28$ m/s is used.

The question is how close to the wall the bulk process values can be found.

Table 4 shows the mass transfer coefficients, mass fluxes, the implied carbon mass flux due to the reaction with CO_2 and H_2O and the needed area for gasification of the 0.226 kg/s char, all as a function of this distance from the wall y, ie. as a function of how close to the wall the bulk values can be found.

For the velocity profile determination, a steepness ratio of 20 between the logarithmic and the polynomial profiles was used. With the gas properties of the above calculation this means $y = 0.010$ m and $y^+ = 73$ and the needed cyclone wall area for gasification of 0.226 kg/s char are from table 4 seen to be 52 m^2. It is unlikely that the logarithmic profile should stretch no longer than to $y^+ = 73$ in a real case so the 52 m^2 must be a lower limit. And further this is for maximum diffusion controlled reaction ie. for no kinetic limitations, a situation not found for the slag surface temperatures of chapter 6.
The result is that for a reactor of reasonable size, the char gasification cannot all take place on the slag surface.

7.2 Char hold up

Data which take kinetic as well as diffusive limitations into account can be obtained from Illerup [12]. For a 4 mm diameter char particle at 1200 °C the time for 95% gasification is given as 50 to 60 seconds depending upon the relative velocity between particle and gas. If the 4 mm particle size and 60 seconds gasification time is describing for the straw char particles in question, the mass hold up for gasification of 0.226 kg/s can be found as $m = 0.226 * 60/(-\ln(0.05)) = 4.5$ kg ie 4.5 kg of actively gasifying char. The density of a loose pile of straw char is 15 to 20 kg/m^3 so the char hold up volume becomes 0.2 to 0.3 m^3. For a reasonably sized cyclone only a fraction of the char shall gasify sticking to the slag. The

Input.

28.0	U	Gas velocity at distance Y	[m/s]
0.175	CCO2	Mass fraction of CO2 at distance Y	
0.145	CH2O	Mass fraction of H2O at distance Y	
1400.0	TG	Process temperatur	[°C]
0.1827	RHOG	Density of bulk gas	[kg/m³]
1519.0	CPG	Cp	[J/kgK]
4.323E-05	GMY	Dynamic viscosity	[kg/ms]
0.08144	GK	Heat conductivity	[W/mK]
3.7005E-04	DCO2N2	Diffusion coefficient for CO2	[m²/s]
4.5873E-04	DH2ON2	Diffusion coefficient for H2O	[m²/s]
0.226	CMPRIK	Char carbon mass flow rate	[kg/s]

Results:

Y [m]	Y+ [-]	UTAU [m/s]	HCO2 [kg/m²s]	JCO2 [kg/m²s]	HH2O [kg/m²s]	JH2O [kg/m²s]	JC [kg/m²s]	A [m²]
1.00E-03	1.04E+01	2.47E+00	5.97E-02	1.05E-02	7.04E-02	1.02E-02	9.65E-03	2.34E+01
2.00E-03	1.85E+01	2.19E+00	4.64E-02	8.12E-03	5.35E-02	7.76E-03	7.39E-03	3.06E+01
3.00E-03	2.60E+01	2.05E+00	4.05E-02	7.09E-03	4.62E-02	6.70E-03	6.40E-03	3.53E+01
4.00E-03	3.32E+01	1.96E+00	3.70E-02	6.47E-03	4.19E-02	6.07E-03	5.81E-03	3.89E+01
5.00E-03	4.02E+01	1.90E+00	3.45E-02	6.04E-03	3.89E-02	5.64E-03	5.41E-03	4.18E+01
6.00E-03	4.70E+01	1.85E+00	3.27E-02	5.71E-03	3.67E-02	5.32E-03	5.10E-03	4.43E+01
7.00E-03	5.36E+01	1.81E+00	3.12E-02	5.46E-03	3.50E-02	5.07E-03	4.87E-03	4.64E+01
8.00E-03	6.02E+01	1.78E+00	3.00E-02	5.25E-03	3.36E-02	4.87E-03	4.68E-03	4.83E+01
9.00E-03	6.66E+01	1.75E+00	2.90E-02	5.08E-03	3.24E-02	4.70E-03	4.52E-03	5.00E+01
1.00E-02	7.30E+01	1.73E+00	2.82E-02	4.93E-03	3.14E-02	4.55E-03	4.38E-03	5.16E+01
1.20E-02	8.55E+01	1.69E+00	2.68E-02	4.69E-03	2.98E-02	4.31E-03	4.16E-03	5.44E+01
1.40E-02	9.77E+01	1.65E+00	2.57E-02	4.50E-03	2.85E-02	4.13E-03	3.98E-03	5.68E+01
1.60E-02	1.10E+02	1.62E+00	2.48E-02	4.34E-03	2.74E-02	3.98E-03	3.84E-03	5.89E+01
1.80E-02	1.22E+02	1.60E+00	2.41E-02	4.21E-03	2.66E-02	3.85E-03	3.72E-03	6.08E+01
2.00E-02	1.33E+02	1.58E+00	2.34E-02	4.10E-03	2.58E-02	3.74E-03	3.61E-03	6.26E+01
2.20E-02	1.45E+02	1.56E+00	2.29E-02	4.00E-03	2.51E-02	3.65E-03	3.52E-03	6.42E+01
2.40E-02	1.57E+02	1.54E+00	2.24E-02	3.91E-03	2.46E-02	3.56E-03	3.44E-03	6.57E+01
2.60E-02	1.68E+02	1.53E+00	2.19E-02	3.83E-03	2.41E-02	3.49E-03	3.37E-03	6.70E+01
2.80E-02	1.79E+02	1.52E+00	2.15E-02	3.76E-03	2.36E-02	3.42E-03	3.31E-03	6.83E+01
3.00E-02	1.91E+02	1.50E+00	2.11E-02	3.70E-03	2.32E-02	3.36E-03	3.25E-03	6.95E+01
3.50E-02	2.18E+02	1.48E+00	2.04E-02	3.56E-03	2.23E-02	3.23E-03	3.13E-03	7.23E+01
4.00E-02	2.46E+02	1.45E+00	1.97E-02	3.45E-03	2.16E-02	3.12E-03	3.02E-03	7.47E+01
4.50E-02	2.73E+02	1.43E+00	1.92E-02	3.36E-03	2.09E-02	3.03E-03	2.94E-03	7.69E+01
5.00E-02	3.00E+02	1.42E+00	1.87E-02	3.28E-03	2.04E-02	2.96E-03	2.87E-03	7.89E+01
5.50E-02	3.26E+02	1.40E+00	1.83E-02	3.20E-03	1.99E-02	2.89E-03	2.80E-03	8.07E+01
6.00E-02	3.52E+02	1.39E+00	1.79E-02	3.14E-03	1.95E-02	2.83E-03	2.74E-03	8.24E+01
6.50E-02	3.78E+02	1.38E+00	1.76E-02	3.08E-03	1.92E-02	2.78E-03	2.69E-03	8.39E+01
7.00E-02	4.04E+02	1.37E+00	1.73E-02	3.03E-03	1.88E-02	2.73E-03	2.65E-03	8.54E+01
7.50E-02	4.30E+02	1.36E+00	1.71E-02	2.99E-03	1.85E-02	2.69E-03	2.60E-03	8.68E+01
8.00E-02	4.55E+02	1.35E+00	1.68E-02	2.94E-03	1.82E-02	2.65E-03	2.57E-03	8.81E+01
8.50E-02	4.81E+02	1.34E+00	1.66E-02	2.90E-03	1.80E-02	2.61E-03	2.53E-03	8.93E+01
9.00E-02	5.06E+02	1.33E+00	1.64E-02	2.87E-03	1.78E-02	2.57E-03	2.50E-03	9.04E+01
9.50E-02	5.31E+02	1.32E+00	1.62E-02	2.83E-03	1.75E-02	2.54E-03	2.47E-03	9.16E+01
1.00E-01	5.56E+02	1.31E+00	1.60E-02	2.80E-03	1.73E-02	2.51E-03	2.44E-03	9.26E+01

Explanation:

Y :	Distance from wall	[m]
Y+ :	Nondimensional distance from wall	[-]
UTAU :	Friction velocity	[m/s]
HCO2 :	Mass transfer coefficient for CO2	[kg/m²s]
JCO2 :	Mass flux of CO2	[kg/m²s]
HH2O :	Mass transfer coefficient for H2O	[kg/m²s]
JH2O :	Mass flux of H2O	[kg/m²s]
JC :	Mass flux of processed carbon	[kg/m²s]
A :	Needed area for gasifying the charflow	[m²]

Table 4. Heat and mass transfer as function of that distance from the wall in which the specified process values are reached.

rest has to find some other place. And if it at this place is not blown effectively through by the gasification agent, more char shall pile up.

8 Discussion

A cyclone gasifier is a mix of an entrained flow and a fixed bed gasifier. Small enough particles are entrained while larger particles are slung to the wall where they form a kind of bed until they have gotten small enough to be entrained. The problems are: how much char must be present for obtaining a certain gasification rate, which form does it have, how shall the cyclone be designed to cope with this.

In a slagging cyclone the surface velocity of the molten slag is low and it might be thought that char sticking to the slag has ample time to gasify. This may also be true but the active surface for this char is no larger than the cyclone wall surface so unless the cyclone is very large this gasification rate shall be rather limited. If more char is fed in than can gasify from the walls, and if the surplus char particles are not gasified before they reach the wall, they will build up a char layer along the wall or a pile of char somewhere in the downstream end of the cyclone.

Because of the turbulent nature of the gas flow such a layer or pile is subject to turbulent bursts which shall entrain especially the smaller or otherwise lighter particles. Very small entrained particles will gasify while larger entrained particles will either be thrown back to the wall or leave the cyclone with the exhaust before they are 100% gasified. Not entrained particles probably get milled into smaller particles as biomass char is rather brittle.

Straw char particles are not spherical. A $10 \times 3 \times 1$ mm piece has in a simple free fall test been seen to behave aerodynamically like a 0.6 mm diameter sphere but it has the mass of a 4 mm and the surface area of a 5 mm diameter sphere. It shall not gasify as quickly as a 0.6 mm sphere but it is entrained as easily and may add to the carry over.

Eventually there shall be mass flow equilibrium, what comes in must get out. Some char gasifies before it reaches the wall, some gasifies from the layer or the pile, some leaves the cyclone with the slag, some gets milled down and becomes entrained and gasifies when suspended and some gets entrained but leaves the cyclone with the exhaust before it is totally gasified.

9 Cyclone proposal

As it is not possible to effectively quantify the cyclone behavior from the above described investigations a size proposal may be based on investigations of existing cyclones. Table 5 lists a number of cyclones, their stoichiometry and power density. It is seen that the power density varies widely and that it is generally lower for straw fired than for coal fired cyclones. Kiørboe [13] concludes from the tests with

	Fuel	Power density [MW m^{-3}]	Stoichiometry	Reference
Ensted power plant	pulverized coal	1.8	1	[14]
TRW	pulverized coal	11.6	0.8	[18]
570 kg/h	pulverized coal	7.9	0.6	[6]
18000 kg/h	crushed coal	5.8	1	[6]
4500 kg/h	plant residue	4.4	1	[6]
Gullair	straw	0.5	2	[14]
Biocomb	straw	1.0	1	[7]
DK-Teknik	straw	3.0	1	[14]

Table 5. Cyclones of different kind.

the DK-Teknik cyclone that this was too small for the specified power ie the 3 MW/m^3 was not achievable for their straw fired cyclone which they tried to run in slagging mode at a modest 1200 °C.

As this project has concentrated on higher temperature operation in order to effectively achieve the slagging mode the cyclone proposal shall be based on a higher power density than those of the non-slagging straw fired cyclones of table 5 but lower than those of the coal fired. A reasonable compromise for further study is believed to be the 3 MW/m^3. For the 20 MW cyclone the proposal is sketched in figure 13.

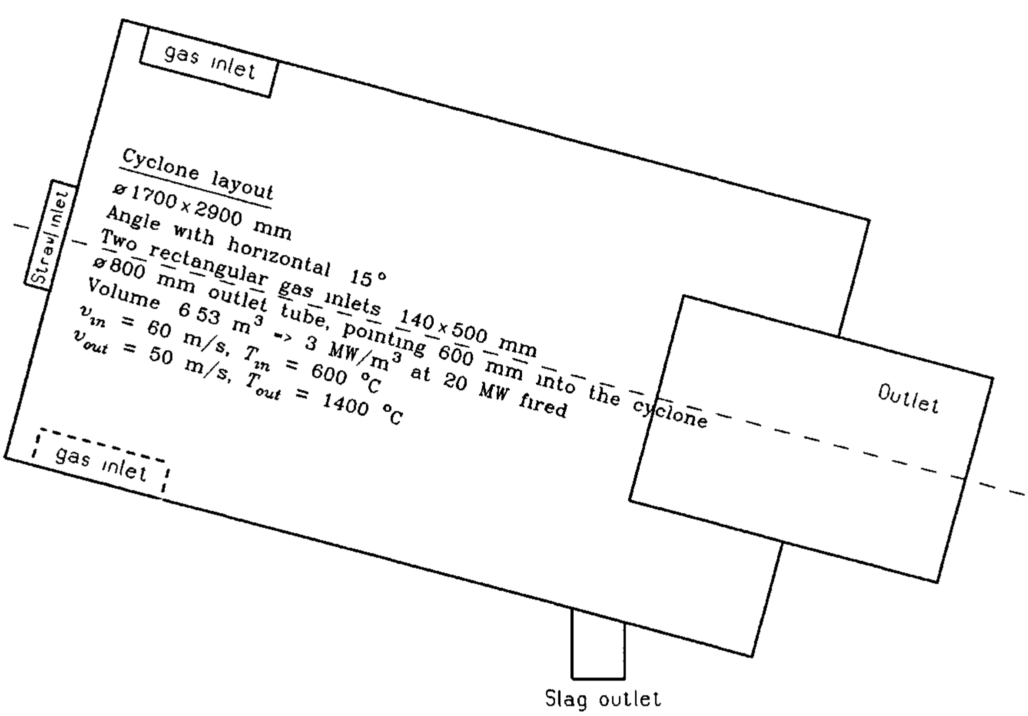

Figure 13. Layout proposal for 20 MW cyclone gasifier.

10 Flow calculations

For the proposed cyclone, a first calculational investigation has been carried out. The gas and particle flows have had to be calculated separately, the gas flow with the commercial CFDS-FLOW3D [1] code and the particle flow with the in house developed PAFCA code [5], and with no feed back from particle code to gas flow code. To obtain a reasonable gas flow it is however necessary in some way to introduce the gas mass source due to the particle devolatilization and gasification.

10.1 Gas flow calculation

Fuel flow

In a cyclone straw gasifier the straw is swept along the walls while devolatilizing and the char shall probably partly pile up in the bottom end of the cyclone and partly follow the recirculating gas flow. The spatial distributions of the devolatilization and the char gasification are uncertain but most of both probably take place in the wall region. For the gas flow calculation the gasification is therefore mimicked by adding the mass flow of the straw as a low velocity gas stream through all of the outer wall area.

Power

Having the correct mass flow the correct density is needed to get the correct velocity. Air is used as model gas and to reach the density of the gasification products with composition as given in table 2 and a temperature of 1400 °C the air has to reach 1600 °C.
Heating of the flow of gasification agent from 600 °C at the entrance to the 1600 °C requires approximately 4 MW of heat. This has to be supplied as a volume source, modelling the power released during the partly burning of the volatiles. As these are expected released and burned close to the wall the power is modelled as a source of 1.2 MW/m^3 for the volume radially positioned outside 600 mm.

Number of dimensions

Fully 3D calculations ought to give the most reliable results but axisymmetric 2D calculations are more easily interpreted and for cyclones with more than one inlet they are usually found to be a good substitute for 3D calculations.
The proposed layout for the 20 MW cyclone gasifier is presented in figure 13 in chapter 9 and the calculational 2D axisymmetric model is shown in figure 14.

Inlets

Inlet 1, 150 mm radius, models the straw inlet but has no other purpose than ensuring that in the subsequent particle flow calculation the particles can enter into a region of non stagnant gas; inlet conditions: $v_z = 0.5$ m/s, $v_r = v_t = 0$, $T = 1600$ °C. Inlet 2 and 4 are the fuel gas inlets: $v_r = -0.475$ m/s, $v_t = v_z = 0$, $T = 1600$ °C, and stretch over the length and perimeter of the cyclone except for the part occupied by inlet 3, the gasification agent inlet: width 52 mm, $v_r = -30.0$ m/s, $v_t = 52.0$ m/s, $v_z = 0$, $T = 600$ °C.

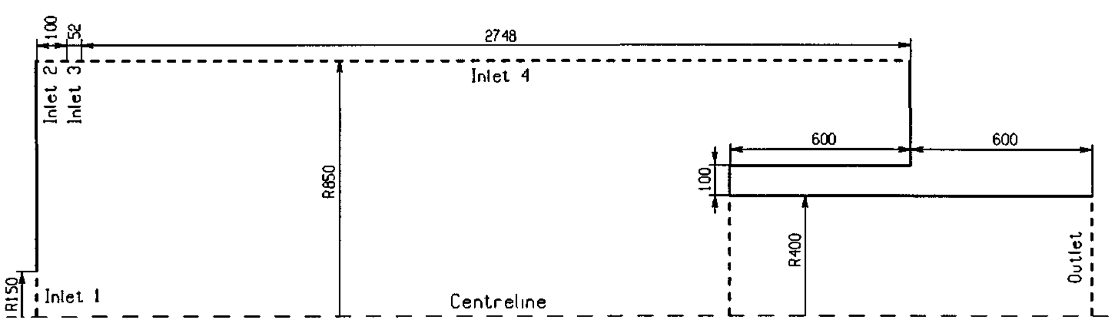

Figure 14. Geometry of calculational model.

Gas flow
For the gas flow calculation the standard $k-\epsilon$ turbulence model has been applied. The resulting streamlines and velocity vectors are shown in figure 15, the axial and radial velocity distributions in figure 16, and the tangential velocity distribution in figure 17 together with the nodalization. It is seen from the streamline figure that practically no recirculation is found. When compared to the streamline plot of the Ohtake case in figure 4 it might be expected that constructional changes could lead to a higher degree of recirculation. The presented Ohtake test case calculation is however based on a Reynolds stress turbulence model and comparison with $k-\epsilon$ based streamlines for the Ohtake case (not presented) shows that just the use of the more advanced turbulence model may enhance the recirculation drastically. All attempts on applying the Reynolds stress model to the actual cyclone case have however led to immediate divergence.

10.2 Particle flow calculations

The PAFCA code has been updated to handle a semi 3D particle calculation in an otherwise 2D environment ie the effect of gravity can now be handled in a non vertical but otherwise 2D case. For the present calculations the proposed 15° angle with horizontal has been used.

Six cases have been calculated, three for spherical particles of constant diameter, 0.05, 0.5, and 5.0 mm respectively, and three for particles with these same numbers as initial diameters but with the gasification modelled as a diameter decrease, 0.067 mm/s, corresponding to 60 s for a 4 mm particle to disappear. The base for this simple model is described in appendix B. The calculation for a particle is stopped when it reaches 0.2 times its original diameter as total burnout is then anticipated . The particle density has in all cases been kept at a constant 120 kg/m^3.

Plots of 50 particle traces for the 0.05 and the 5.0 mm constant diameter cases are shown in figure 18. While all except one of the 5 mm diameter particles end at the wall where they are stopped on a low velocity criteria, 60% of the 0.05 mm particles pass the outlet. This behaviour is almost the same for the decreasing radius cases, although a part of the small particles gasify completely and only around 45% reaches the outlet, more or less gasified. For the 0.5 mm particles figure 19 compares the two cases, constant and decreasing diameter. Here it is seen that none of the 50 constant diameter particles traced escapes while many of

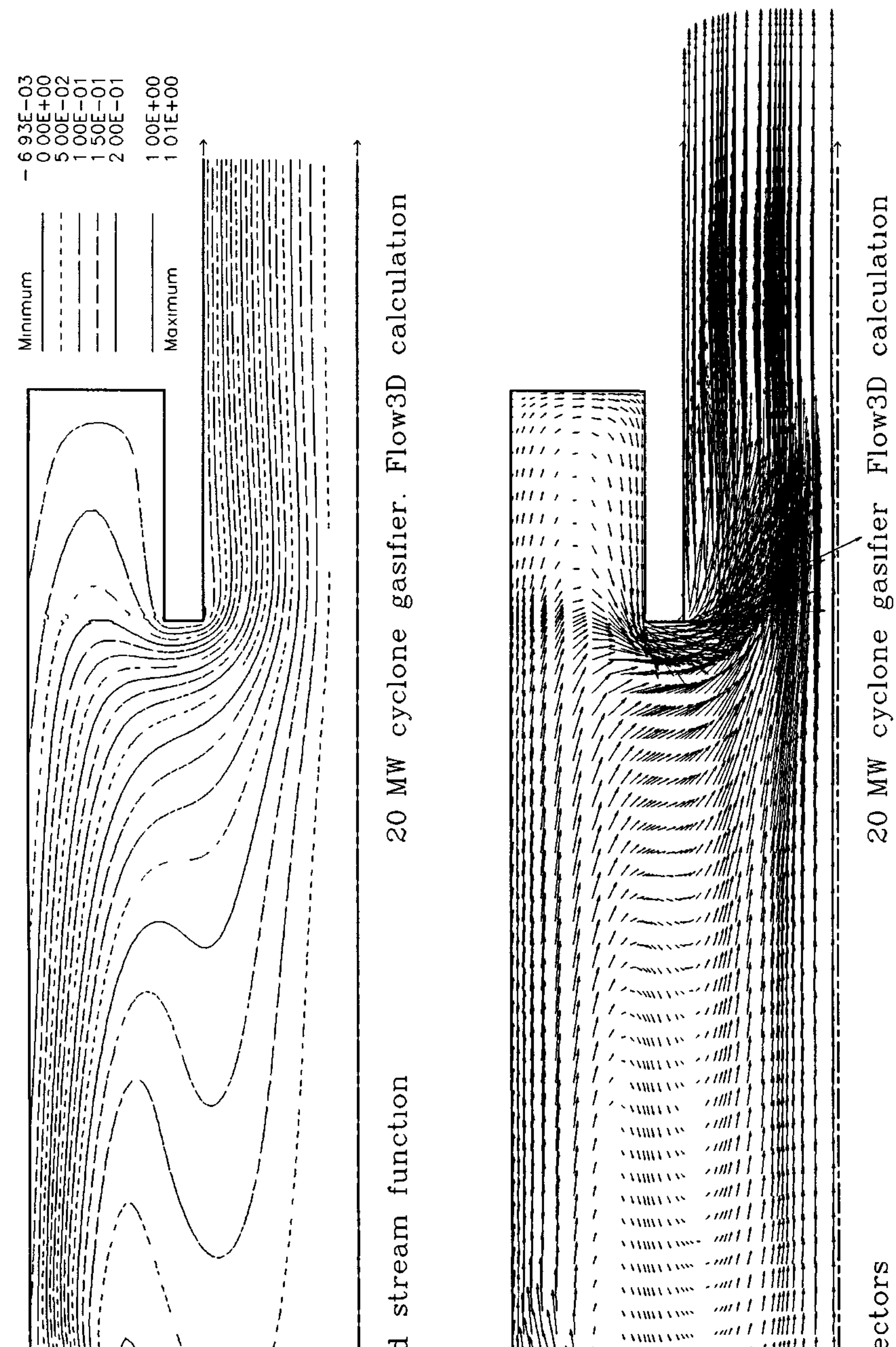

Figure 15. Gas flow. Left: streamlines. Right: velocity vectors.

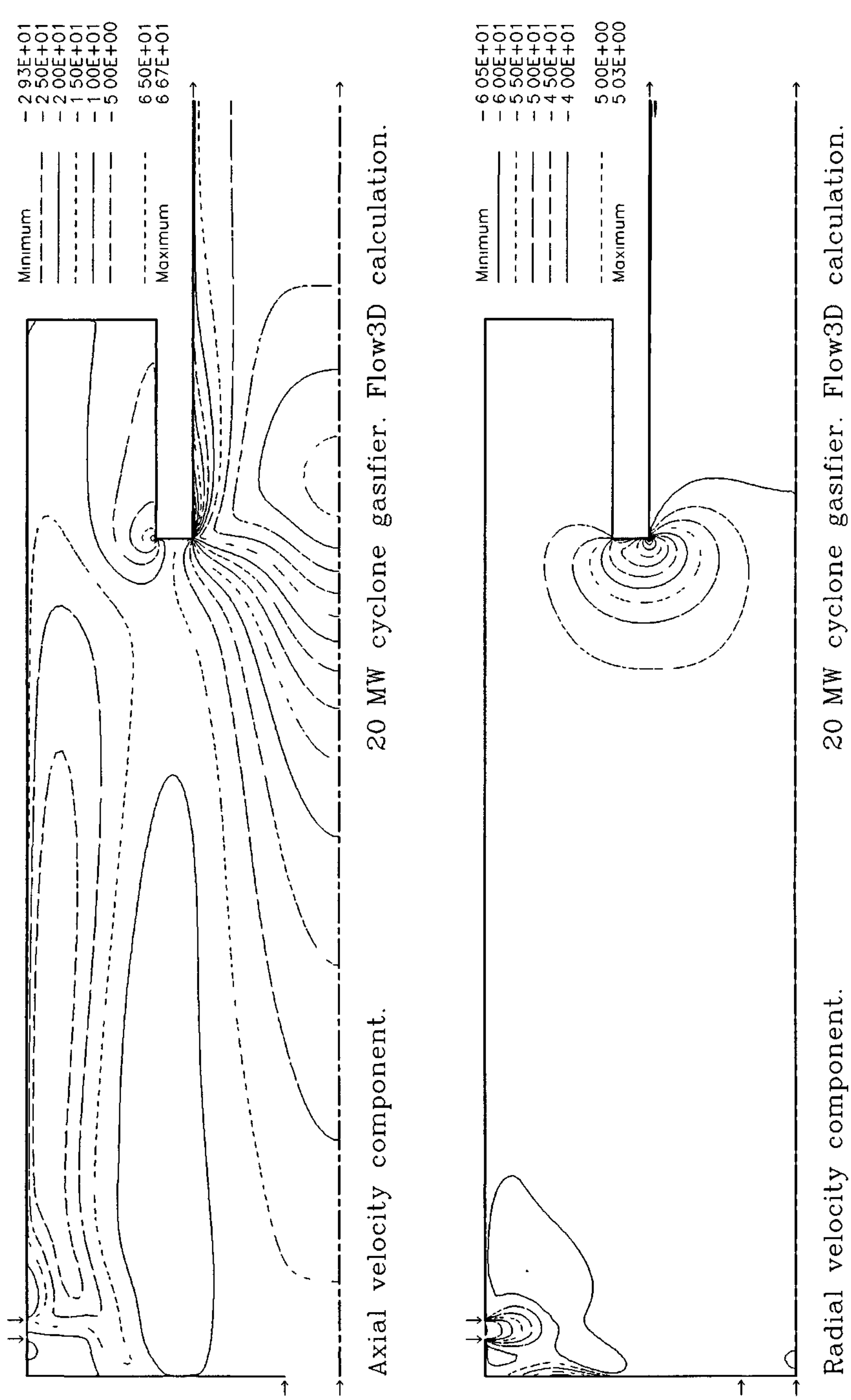

Figure 16. Gas velocities. Left: axial component. Right: radial component.

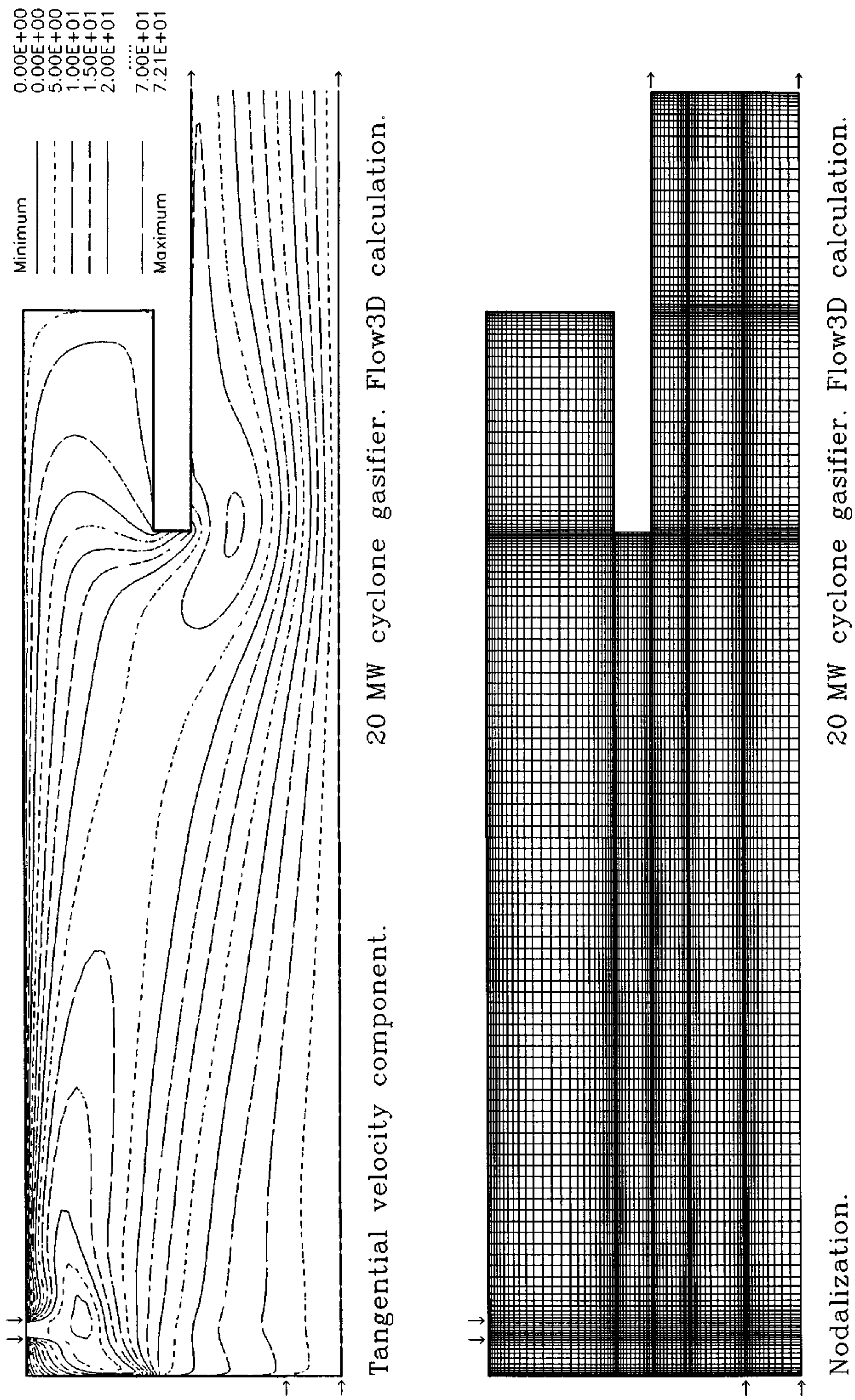

Figure 17. Left: tangential gas velocity component, right: nodalization.

the partly gasified particles do. Those which escape are all below 0.3 mm. And it is interesting to see how this size particles circulate in the bottom pocket. This is the picture the author expects to find in a real cyclone gasifier also for the larger particles.

There are large calculational uncertainties: 1) The size distribution of the feed and how fast straw char breaks up and into which size particles are all unknown and here not at all modelled. 2) As described in chapter 7 the char filling the slag surface does not gasify at a rate equaling the feeding rate. The surplus feed finds no place to stick but anyway interacts with the wall or rather with the char at the slag surface. How is unknown but here modelled as a simple wall reflection with the particle speed decreased a factor $\sqrt{10}$ ie the kinetic energy decreased to a tenth. When the velocity this way has fallen below 5 mm/s the calculation is stopped. 3) As mentioned above the particle carrying gas flow should be determined better.

These calculations together with the fact that char particles may behave aerodynamically as much smaller spheres than those equivalent to their masses, do indicate, however, that the proposed design may lead to a substantial carry over of char.

11 Conclusion

The capability of two commercially available fluid dynamics codes to do cyclone calculations has been investigated and although they both underpredict the swirl velocity it is believed that they both can be used for further gas phase calculations. There is however an essential difference between the two codes, the CFDS-FLOW3D code is an in house code, while the FLUENT code resides at Fluent Europe in Sheffield, England. The work with this latter code is therefore much less flexible and is limited to the specification of the case and the treatment of the resulting data. This provides much less insight into the goodness of a calculation for which no data is at hand.

Different elements influencing the design of a 20 MW as fired slagging cyclone straw gasifier have been investigated, including slag flow, heat flow through the slag and wall and gasification possibilities for char sitting in the slag. The heat and mass flux calculations need a gas velocity field as base and for this part of the work this field has been limited to a profile for the tangential velocity component.

To simplify the slag flow calculation the cyclone wall has been assumed vertical. The relation between the slag flow and the heat transport from the cyclone interior through the slag to an air heater annulus surrounding the cyclone has been investigated. The calculated heat transfer is mainly limited by the heat transfer coefficient on the annulus side why the steel temperature gets rather high although the surface of the slag from a gasification point of view stays relatively cool. A more viscous slag sets up a thicker slag layer with a higher slag surface temperature and a lower steel temperature but even for an extremely viscous slag

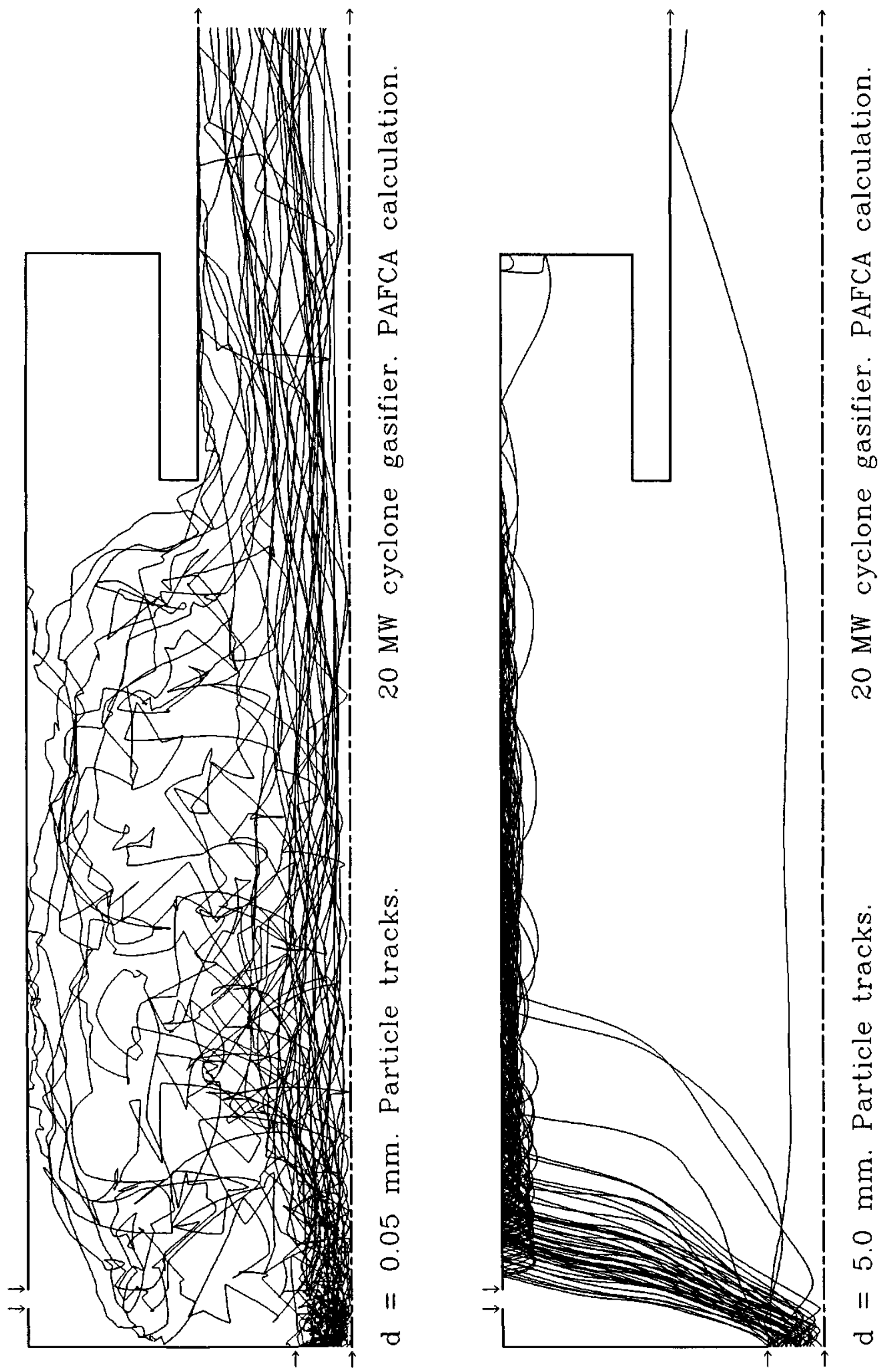

Figure 18. Particle tracks. Left: 0.05 mm diameter particles, right: 5.0 mm diameter.

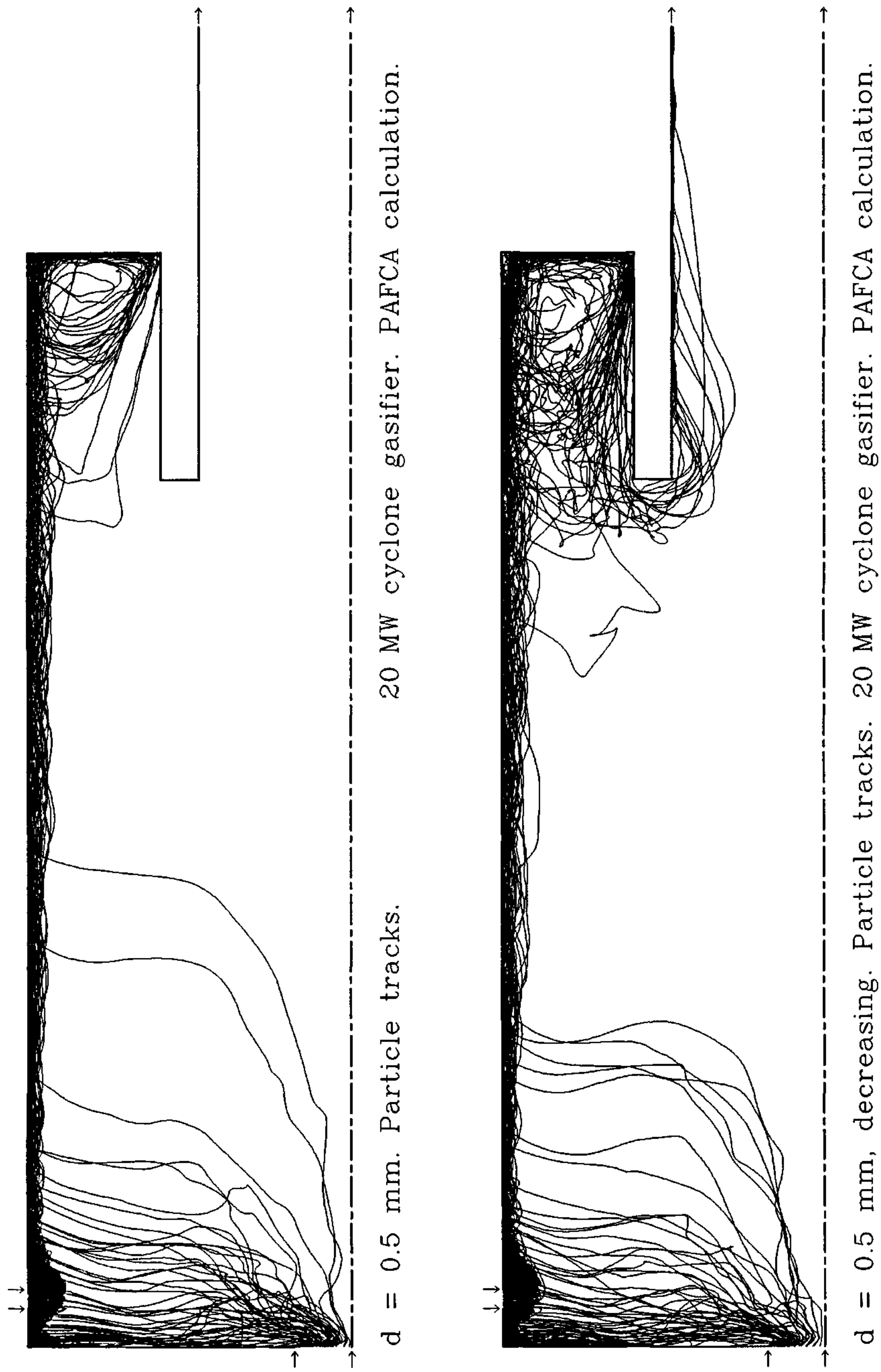

Figure 19. Particle tracks. Particle diameter 0.5 mm, left: constant, right: decreasing.

a steel temperature about 800 °C is found.

The calculated mass transfer of gasification agent to the char at the slag surface is like the convective heat transfer found rather small. If all char has to gasify sitting at the slag surface a very large cyclone therefore shall be required. The problem is that when the char sits at top of the slag, it is the cyclone wall area that counts and not the particle area, the gases have to diffuse from the bulk to the cyclone wall and not from all sides towards suspended particles. For a reasonably sized cyclone it can therefore be stated, that not all char gasification can take place at the slag surface, most has to take place from char more or less in suspension.

The layout for a 20 MW reasonably sized cyclone has been proposed and a calculational investigation has been initiated. The use of the standard $k-\epsilon$ turbulence model however seems to have created a not quite realistic gas flow pattern as base for the particle flow model which in turn also needs more sophistication. The calculations nevertheless indicate the possibility of a relatively large carry over of only partly gasified char.

Carrying on

Calculations of the gas flow for the proposed cyclone and derivatives employing a Reynolds stress turbulence model should be made in order to find a form giving the highest possible degree of recirculation.

For the particle tracking the model ought to implement the particle size as a restriction to how close a particle can come to a wall as particles treated as points and ending at the wall see no gas velocity and stop. At best the particles should also be influenced by the local particle concentration.

For a larger project a more sophisticated particle gasification model could be included, and two way information interchange with the gas flow code might provide this latter with the necessary source terms for the energy and constituent balances and the particle model with the actual species concentrations around the particles. A succession of calculations would be needed for approaching steady state conditions.

A way to get some real knowledge is to perform some experiments. A cold flow experiment in a reasonably sized cyclone with transparent ends shall provide good data on the structure of the particle laden flow, on how the straw char distributes in the cyclone, and on the size distribution of the carry over, all as function of the inventory and of the size distribution of this. And the influence of design changes can be readily obtained as such changes are easily made on a cold model.

Based on such results a hot model could be designed and tested.

References

[1] FLOW3D. Release 3.2: User Guide. CFD Department, AEA Industrial Technology, Harwell Laboratory, United Kingdom, 1992.

[2] International Glass Data Base, Version I. New Glass Forum, Tokyo, Japan, 1991. On CD-ROM.

[3] Stig A. Andersen. *Måling af viskositet af slagge fra biomasse/kul forgasnings/forbrændingsanlæg.* Risø-I-832(DA). Risø National Laboratory, 1994. In Danish.

[4] Verdat S. Arpaci and Poul S. Larsen. *Convection Heat Transfer.* Prentice-Hall, 1984.

[5] Poul Astrup. *Udvikling af EDB-model for stationær turbulent 3-D gas-partikel strømning. PAFCA, PArticle Flow CAlculations. Programbeskrivelse.* Risø-M-2759. Risø National Laboratory, Denmark, 1988. In Danish.

[6] John S. Barnhart and Normand M. Laurendeau. Pulverized coal combstion and gasification in a cyclone reactor. 1. experiment. *Ind. Eng. Chem. Process Des. Dev*, 21(4):671–680, 1982.

[7] Biocomb AB. Sweden. Brochure.

[8] Jan Fjellerup. *System Modelling of Integrated Gasification Combined Cycle Power Plants.* Risø-R-686(EN). Risø National Laboratory, Roskilde, Denmark, April 1993.

[9] A. D. Gosman and F. J. K. Ideriah. *TEACH-2E: A General Computer Program for Two-Dimensional, Turbulent, Recirculating Flows.* Department of Mechanical Engineering, Imperial College, London, 1976. Revised by M. P. Arnal, Department of Mechanical Engineering, University of California, Berkeley, 1983. Report No. FM-83-2.

[10] S. Hadvig. Termisk stråling for ingeniører. Noter til II. Laboratory of Heating and Air-Conditioning, Technical University of Denmark, 1987. In Danish.

[11] HECBIO. Highly efficient conversion of biomass to power and heat. Final report. JOU2-CT93-0434, 1995. Not published.

[12] Jytte B. Illerup. JOULE II HECBIO, JOU2–CT93–0434, Combustion and Gasification of Biomass, Progress Report. Risø National Laboratory, January 1995. Not published.

[13] Lars Kiørboe. *Cyklonfyring af halm. 2. delrapport. Bygning af anlæg. Forsøgsresultater.* EM-journal no. 1433/87-5. dk-TEKNIK, April 1990. In Danish.

[14] Steen Otterup Nielsen. *Cyklonfyring af halm. 1. delrapport. Cyklonfyringsteknik.* EM-journal no. 1433/87-5. dk-TEKNIK, September 1988. In Danish.

[15] K. Ohtake and Y. Nakatake. Cold model study of flow field and slag rejection efficiency in cyclone slagging combustor. In: J.R. Lloyd and Y. Kurosaki, editors, *Proceedings of the 1991 ASME JSME thermal engineering joint conference. Volume 5*, pages 239–244. 1991.

[16] Peter Stoholm and Mogens Kirkegaard. Eksperimentel bestemmelse af halmknæs udbrændingstid. Risø National Laboratory, May 1992. In Danish. Not published.

[17] Bjørn Teislev *et al.* Highly efficient conversion of biomass to power and heat. ENS-1323/93-0022, 1995. Not yet published.

[18] TRW. *Coal Combustion Research Report.* TRL-5. TRW Energy Products Group, Combustion Business Unit, October 1986.

A Logarithmic wall profiles

At a wall bounding turbulent flow the so called log-law of the wall applies ie the velocity profile in the neighbourhood of the wall is logarithmic. In the innermost layer, the so called laminar sublayer, the profile is linear. With u designating the gas velocity at the distance y from the wall, τ_w the wall shear stress, ρ the gas density, μ the gas dynamic viscosity and $\nu = \mu/\rho$ the gas kinematic viscosity, and with the definitions:

$$U_\tau \equiv \sqrt{\frac{\tau_w}{\rho}} \tag{A.9}$$

$$y^+ \equiv \frac{y\,U_\tau}{\nu} \tag{A.10}$$

$$u^+ \equiv \frac{u}{U_\tau} \tag{A.11}$$

the following equations describe the turbulent velocity profile near the wall [4]:

$$u^+ = \begin{cases} y^+ & \text{for} \quad y^+ < 5 \\ 5\ln(0.54\,y^+) & \text{for} \quad 5 < y^+ < 30 \\ 2.5\ln(9\,y^+) & \text{for} \quad 30 < y^+ \end{cases} \tag{A.12}$$

Here shall only the latter expression be used. It is normally written:

$$u^+ = \frac{1}{\kappa}\ln(E\,y^+) \tag{A.13}$$

where $\kappa = 0.4$ and $E = 9$. What is really modelled here is the turbulent momentum diffusion:

$$\tau_t = \tau_w = \rho\,\overline{u'v'} \equiv \rho\,U_\tau^2 \tag{A.14}$$

Turbulent diffusion of heat and mass can be modelled equivalently:

$$q_t = q_w = \rho\,C_p\,\overline{u'T'} \equiv \rho\,C_p\,U_\tau\,T_q \tag{A.15}$$

$$J_t = J_w = \rho\,\overline{u'\gamma'} \equiv \rho\,U_\tau\,\gamma_J \tag{A.16}$$

whereby T_q and γ_J are defined. For the heat transfer the equations corresponding to eqs. A.11 and A.13 are

$$T^+ \equiv \frac{T - T_w}{T_q} \tag{A.17}$$

$$T^+ = \sigma_T\left(\frac{1}{\kappa}\ln(E\,y^+) + P_T\right) \tag{A.18}$$

where

$$\sigma_T \approx 0.9 \tag{A.19}$$

$$P_T = 9.0\left[\left(\frac{Pr}{\sigma_T}\right)^{0.75} - 1\right]\left[1 + 0.288\exp\left(-0.007\,\frac{Pr}{\sigma_T}\right)\right] \tag{A.20}$$

Pr is the Prandtl number, σ_T is the turbulent Smith-number for heat diffusion ie the turbulent Prandtl number and P_T an empirical correction [4].
For the mass diffusion the equivalent equations become

$$\gamma^+ \equiv \frac{\gamma - \gamma_w}{\gamma_J} \tag{A.21}$$

$$\gamma^+ = \sigma_\gamma \left(\frac{1}{\kappa} \ln(E\, y^+) + P_\gamma \right) \tag{A.22}$$

Here

$$\sigma_\gamma \approx 0.75 \tag{A.23}$$

$$P_\gamma = 9.0 \left[\left(\frac{\nu}{D\, \sigma_\gamma} \right)^{0\,75} - 1 \right] \left[1 + 0.288 \exp\left(-0.007 \frac{\nu}{D\, \sigma_\gamma} \right) \right] \tag{A.24}$$

where D is the diffusivity of the species in question.

The velocity profile can be determined from a known set of u and y, the temperature profile from a set of $T - T_w$ and y and the mass fraction profile from a set of $\gamma - \gamma_w$ and y. The heat and mass transfer coefficients defined as

$$h_{wT} \equiv \frac{q_w}{T - T_w} \tag{A.25}$$

$$h_{w\gamma} \equiv \frac{J_w}{\gamma - \gamma_w} \tag{A.26}$$

can be determined as

$$h_{wT} = \frac{\rho\, C_p\, U_\tau}{T^+} \tag{A.27}$$

$$h_{w\gamma} = \frac{\rho\, U_\tau}{\gamma^+} \tag{A.28}$$

B Burning of straw

The volume of burning straw pieces has been measured as a function of time by simple but not so accurate application of a ruler to two series of video pictures from experiments on burning of straw knees [16]. The two series are called PSE and MMMA and the latter is shown in figure 20.

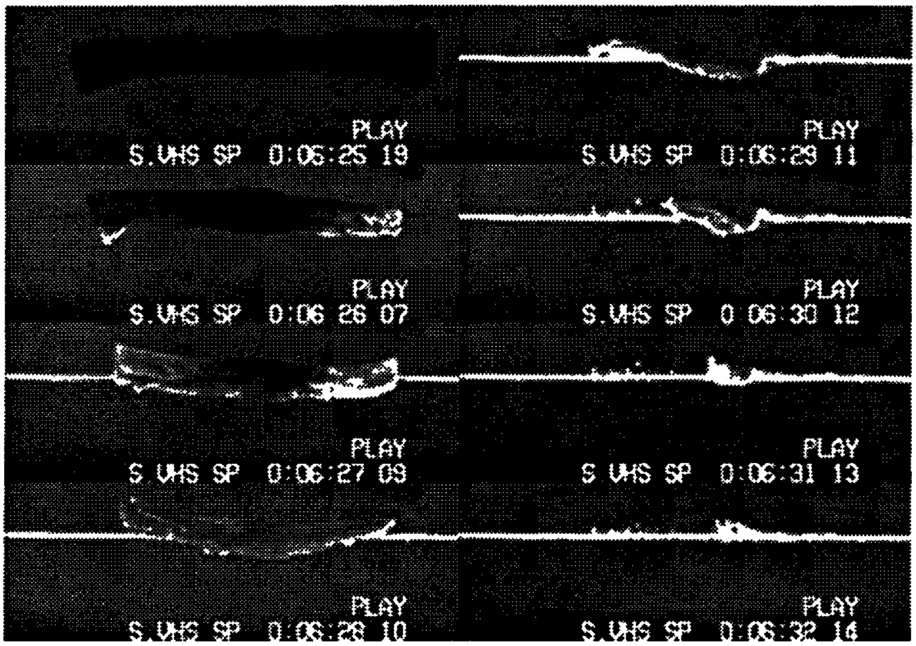

Figure 20. Video pictures of the MMMA series experiment.

The experiments were characterized by constant conditions, for the MMMA series 1230 °C, 4% O_2 and 2.8 m/s gas velocity relative to the straw, and it has been found, that the process was totally diffusion controlled. For the PSE series which was a pretest series, the conditions are not well known.
In figure 21 two functions: an exponential volume decay and one which corresponds to a constant volume per surface burn off, are compared to these volume measurements. The latter best correlates the data. It reads

$$V = V_o \left(1 - \frac{t}{t_{bo}}\right)^3 \tag{B.29}$$

where V_o is the volume at time $t = 0$ and t_{bo} is the burnout time. This indicates that for a diffusion controlled process the volume can be described by a single length l, as for a sphere, so that a burn out model can be simplified to a model for dl/dt. For the picture series experiments this becomes a constant given as

$$\frac{dl}{dt} = -\frac{l_o}{t_{bo}} \tag{B.30}$$

One thing is the volume, another the density. For a simple model it may be believed that the devolatilization, which is very fast for straw, does not influence the measurable volume, only the density, while the char burning follows the above described shrinking core model without affecting the density.

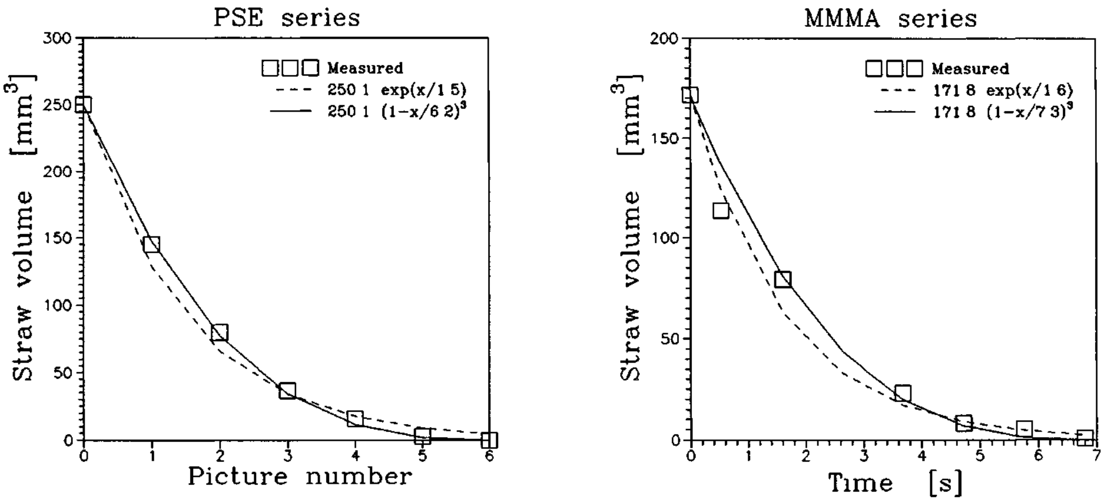

Figure 21. Two functions compared to measured volumes of burning straw pieces.

Bibliographic Data Sheet **Risø–R–833(EN)**

Title and author(s)			
Cyclone Gasifier for Biomass Preliminary Investigations Poul Astrup			
ISBN 87–550–2089–5			ISSN 0106–2840
Dept. or group Department of Combustion Research			Date July 1995
Groups own reg. number(s)		Project/contract no. ENS-1323/93-0022 JOU2-CT93-0434	
Pages 40	Tables 5	Illustrations 21	References 18

Abstract (Max. 2000 char.)

Aiming at the design of a 20 MW as fired slagging cyclone gasifier for biomass, it has been investigated how biomass can or have to behave in such a device. This has included calculations for the slag flow, the heat loss, the gasification limits for char sitting in the molten slag surface, and fluid dynamics calculations for the gas and particle flows in a test case and in a proposed design. It has been found that it is unlikely that the char sitting in the slag surface can gasify at a rate equaling the feeding rate unless the cyclone is very large, that a high amount of char therefore has to stay in suspension somewhere in the cyclone and for a long time and that this may lead to a substantial carry over for the proposed design.

Descriptors INIS/EDB

BIOMASS; CYCLONE COMBUSTORS; FLUID FLOW; GASIFICATION; HEAT FLOW; SLAGS; STRAW

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- *Energy technologies for the future*
- *Energy planning*
- *Environmental aspects of energy and industrial production*
- *Environmental aspects of plant production*
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Key Figures

Risø has a staff of just over 900, of which more than 300 are scientists and 80 are PhD and Post Doc. students. Risø's 1995 budget totals DKK 476m, of which 45% come from research programmes and commercial contracts, while the remainder is covered by government appropriations.

Risø-R-833(EN)
ISBN 87-550-2089-5
ISSN 0106-2840

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